Radar, Insect Population Ecology, and Pest Management

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16 Abstract

These proceedings include twelve contributed papers and the product of four working groups that either directly or indirectly address ways in which radar might be used as an observing tool for entomological studies and pest management in the United States. Population processes of flying insects are reviewed with emphasis on species where migration is a clear component of their life history. Known radar capabilities as they relate to insect detection and flight study are presented through several papers that relate actual field studies, and the prospects for using various types of radars are considered.

The working groups developed a variety of project plans for the future use of radar as a field tool for insect flight studies. Specific recommendations are presented for entomological projects, a large scale pest management program, and various aspects of radar hardware development and data analysis necessary for effective implementation of the radar tool for insect oriented programs.

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EXECUTIVE SUMMARY

This workshop was convened, through mutual agreement between the USDA/SEA-AR and NASA/WFC, in order to familiarize a group of radar scientists, pest managers, entomologists,and meteorologists with the state-of-the-art of radar entomology, and to produce a document with program recommendations for the realistic application of radar to insect ecology studies and pest management. From May 2-4, 1978 a multi-institutional body of forty scientists from Canada, Great Britain, and the United States attended this workshop and developed these recommendations, with no specific charge to direct them to any particular governmental agency. The detailed recommendations in the Summary, and in each session report, are useful for directing ongoing programs, as well as for developing new programs.

There is no question that the use of radar in pest management can potentially lead to important changes in pest management practices, with annual benefits to society of hundreds of millions of dollars. Specific attention was called to the fall armyworm: a moth only capable of surviving southward from the southernmost regions of the United States. By September each year close to $500,000,000 damage to agriculture is done as this species migrates northward to Canada. However, migration is a significant factor in the population dynamics of many more species of pest insects than the fall armyworm. Yet for most such insects migration is not adequately understood, even though such an understanding is necessary to reduce effectively the annual loss to agriculture of billions of dollars. The basic problem lies in the present lack of techniques to observe this migration.

Radar is a remote sensing tool that, in many situations, observes insect flight. However, radar technology is complex and foreign to the entomologist and pest manager and, hence, not easily adapted by them to their needs. Nor is the present configuration of any commercial radar system appropriate to the study of insect flight. Use of radar by entomologists will require system developments through a multidisciplinary activity.

The output of this workshop includes fourteen general project outlines; four are radar oriented, the other ten entomology oriented. Together these form the basis of a well integrated radar entomology program. Thus, if a tentative decision can be reached to consider a substantial on-going program in radar entomology, a planning team can (and should) be convened to develop the detailed plan of work, including costs and personnel requirements necessary to achieve the project objectives.

It is clear that the benefits to society will be greatest if these individual projects are addressed within the context of a more comprehensive radar entomology program. The effective transfer of radar technology to the users will require administrative leadership to develop and support economically significant field demonstrations of the technology. Support must continue over a time frame sufficient to ensure that a constituency of radar entomologists develops

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WORKSHOP SUMMARY WITH RECOMMENDATIONS

This three day international workshop consisted of one day of formal paper presentations, followed by two days of working group meetings. The newness of the idea of using radar as an entomological tool, combined with the disparate backgrounds of the participants, resulted in a workshop stimulated by the realization that a new discipline of radar entomology may develop, with significant potential for contributing both to basic entomology and to the critical area of pest management.

Attendees from each represented discipline (entomology, pest management, meteorology, radar engineering, physics and management) recognized that basic research projects are of primary importance for realizing the breadth of potential for radar. The British have already demonstrated that pest management can benefit from using radar technology. Such demonstration, in fact, stimulated the organization of this workshop. However, U.S. scientists and administrators need one, or more, clear demonstrations that radar technology can provide tools of general application to a wide range of problems. The false impression needs to be avoided that radar is very limited in value, with only the most extreme pest management situations benefiting.

Against this background the reports from the working groups are significant; when combined with the presented papers a valuable document results that is useful to administrators when planning the organization of general program areas, and to scientists when planning specific projects. Within the group reports are useful project descriptions and recommendations for a course of action over the next 5 to 10 years. At the same time, the contributed papers provide a useful introduction to the relevant aspects of insect migration, pest management, meteorology, radar technology and radar entomology. The brief Bibliography at the end of the report affords readers with an easy entry into disciplines unfamiliar to them.

Leadership for the infusion of high level technology into pest management and entomological research must come from the U.S. Department of Agriculture. However, the ideas and recommendations that this document contains are not directed to a specific government agency.

An immediate fundamental need is for an administrator to establish a mechanism whereby radar scientists and entomologists can explore the potential capability and importance of radar as an entomological tool. Such a mechanism is particularly important in the near term since no focal point of activity exists; hence, a high level administrative advocate is needed to help maintain program continuity over a time span sufficient to insure the mature development of the technique. The question of the level of financing, and exact management structure required to effect various proposals, is left open. Even so, some university participants strongly expressed their desire that disbursement of some funds

for specific projects be done through a competitive grant process with peer review.

Three general program approaches are either implied or directly emphasized in the four group reports. The Field Program Development Group devoted its total effort to presenting a large, cohesive, narrowly focused project with a single goal - the strategic control of lepidopterous pests that overwinter in the most southern areas of the U.S. and migrate north with developing spring to infest almost fifty percent of the United States.

This man-on-the-moon goal oriented approach is in striking contrast to the approach required to implement most of the projects. Radar technology is viewed by most participants, not only as a highly seminal area for entomologists to pursue, but also as an area that is still tentative for most implied applications. With mostly promise, and a fair amount of uncertainty of future direction, radar entomology needs many small diverse projects, with administrative emphasis on the grant approach through competition.

The final program approach is based on establishing three or four focal points of activity in typical, but different, areas of the country. This approach combines elements of the previous two, while offering a high degree of flexibility in adapting new techniques to regional problems.

The disciplinary composition of teams involved in radar entomology studies and operations was discussed. In this regard the Canadian experience in the spruce budworm program is documented. A specialist chosen from radar science, entomology, or meteorology needs a sufficient understanding and appreciation of the other specialties to be able to pose useful questions outside of their field, while at the same time recognizing their own limitations in attempting single-handed answers. The meteorological component needs to include a research micrometeorologist with a thorough knowledge of boundary layer processes and a meteorologist with both synoptic and local forecasting experience.

In addition to the above recognized disciplines two other specialists may be essential. The first is a dynamic biogeographer to continuously collate, analyze, map, and integrate all available information on pest's distribution, environment, movement, etc. The second specialist is the airborne mission scientist for in-flight monitoring, mapping, preliminary interpretation of data, and progressive amendment of the current flight plan.

Large projects are easy to plan at a general level. The implication is always present that the details will take care of themselves. Most participants recognize that the technological approach to many problems is not apparent. And, in fact, it is not clear that a technological solution (i.e., using radar) will work for any specific project. One suggestion is that a useful product is a complete listing of available radar systems, and important subsystems, that are either commercially available, or available through government channels on surplus or loan. Such a listing would be particularly valuable at this time; one important need in the entomology - user area is the ability to do quick experiments to demonstrate what can be done with minimal effort. Such observations should clearly be made, and at a minimal cost, or else some entomologist won't feel justified in

committing·the substantial resources necessary to insure large scale technical success using radar.

The working groups recognized that a) a number·of the most important insect pests of U.S. agriculture, forestry, and public health disperse long distances; b) a considerable variety of radar systems already exist with the potential for delineating insect movement and for determining causal factors; and, c) a substantial saving from insect depredation is likely to be realized from a well supported program in the development and use of radar to study insect movement. Accordingly the workshop recommended that high priority be assigned to assembling and supporting effective groups of scientists for this purpose for at least a decade.

Explicit recommendations were submitted by three of the four working groups; the fourth group recommendations being implicit in the projects they developed. Because time during the workshop did not permit close interaction between groups, duplication of recommendations occurred. This section eliminates duplication and organizes these recommendations into three categories that challenge both administrators and research workers in radar and entomology. Specific details of the recommendations can be found in the group reports.

Recommendation I: Administrative Leadership

Administrative leadership is needed to develop and support programs, and establish cooperative working relationships between state, federal, and private organizations that lead to an in-depth radar entomology program that
(a) uses the best presently available radar equipment; and,
(b) uses one, or more, teams of entomologists, meteorologists and radar scientists to conduct interdisciplinary programs, and develop additional state-of-the-art programs that take maximum benefit of developing technologies.

Recommendations II: Existing Technology

Existing technology (entomological, meteorological, and radar) needs to be used to study insect flight; specifically, ·
(a) by monitoring the dynamic variations in airborne insect densities at strategic
  · geographic locations, times, and altitudes;
(b) by studying the role of meteorology in transporting and/or concentrating insects due to various wind flow patterns;

(c) by characterizing diffusion patterns and the fate of insects released from aircraft during mass release operations;

(d) by characterizing airborne insect populations over fields saturated with pheromone, and response behavior around point sources of pheromone;

(e) by studying the biological and environmental factors that initiate, sustain, and terminate insect flight;

(f) by using airborne radar to define the extent, height distribution, and densities of airborne insects during meteorological events that transport or concentrate significant populations;

(g) by evaluating the damage potential of migrating insects detected by radar or other detection methods;

(h) by using existing meteorological, military, and civilian radars whenever possible and appropriate.

More specifically existing technology needs to be used to,

(i) study the movement of fall armyworms across Florida and northward,

(j) study annual movement of insects such as Heliothis species and cereal aphids from southern to northern U.S.; and,

(k) study the passive dispersal of gypsy moth larvae (wind-blown on a strand of silk) and of adult male gypsy moths (females do not fly).

Recommendation III: New Technology

Advanced technology for radar entomology needs to be meaningfully developed and maintained through systematic programs that

(a) determine the total information about insects realistically available from a radar signal;

(b) use radar information and signature analysis techniques to classify airborne insects;

(c) determine optimum configurations of ground-based and airborne radars. These studies should be directed toward accomplishing specific missions and include associated recording, processing, and display of radar information;

(d) detect and characterize insect activities near or within plant canopies;

(e) provide an airborne radar for use in light aircraft;

(f) provide a simple, easy-to-use, and portable entomological radar;

(g) assist development of insect transport and integrated pest management models that use flight dispersal data obtainable from radar.

INTRODUCTION

Many insects greatly benefit human society, for example as pollinators and fascinating objects of scientific study. But, it is mainly because of the economic losses caused by some insects that public funds are made available for their study. In the United States insects destroy, on the average, about 13 percent of the potential harvest in spite of diligent efforts in plant and livestock protection. These direct losses exceed $7 billion per year. Ecological disruptions and human hazards of current insect control practices are of widespread concern. For these reasons the number of scientists concerned with insects compares equally with those in wildlife management and fisheries; the memberships of the Entomological Society of America, the American Fisheries Society and the Wildlife Society being 7200, 6000 and 7500, respectively.

The movements of insects have been the subject of much research, speculation, and controversy. In some cases for the same species, insect movement has been characterized as either random or directional, independent of population density or dependent on density, appetential or non-appetential, little influenced by atmospheric processes or greatly influenced by them, and either short range or long range. Clearly entomologists need to increase their understanding of insect movements. This is of utmost importance in order to quantify population changes and to design strategies to manage insect pests better.

During the past decade British scientists, in cooperation with entomologists on various continents, have taken the lead in developing the use of radar as an instrument to study insect movements. Over the last year it became evident to the USDA and NASA that American scientists need to be better informed of this development and, because of the large United States technological experience and entomological need, to investigate ways to promote interdisciplinary programs in radar entomology.

Accordingly, the USDA requested that NASA participate in a joint workshop, the results of which are these proceedings. A "workshop" format for the meeting was chosen to encourage interdisciplinary communication and an interdisciplinary formulation of problems. Since neither radar technologists nor entomologists were expected to have knowledge of their counterparts' discipline, we used the first day for formal presentations. These presentations were deliberately simplified and tutorial to permit comprehension of major concepts by scientists that were not from the speakers' discipline.

A specific purpose for the workshop was formalized and sent to all invitees along with their invitations. This purpose is reproduced following the Introduction. To achieve this purpose four working groups were organized to work concurrently. One group defined entomological research problems potentially amenable to radar study; a second group investigated potential radar applications to pest management situations. Specific consideration of radar technology and how it might be applied to entomology was assigned

to the third group; while the fourth group developed an interdisciplinary field program that would demonstrates a major application of radar to an entomological problem.

We recognized that making the assignments concurrent was not the best way to proceed. Logic demanded the first two groups develop the projects that the radar group could then evaluate and subsequently suggest one, or more, radar systems (including a network) that might contribute to problem solutions. The fourth group would then select one problem and write an overall project proposal - as it were -that some funding source might act upon. Time, however, did not permit such an approach. We hoped that by choosing at least one research entomologist, one pest manager, one radar system specialist and one meteorologist for each group, projects considered would be sufficiently similar that a common theme could be extracted by the editors. To encourage commonality of thought we asked that first consideration be given to the pink bollworm, the corn earworm, the gypsy moth, the spruce budworm, and the fall armyworm.

Because of the newness of the idea of using radar for entomological purposes a common theme did develop - basically around the most obvious cases where radar might be a useful tool. The British and Canadian participants were particularly helpful. Their real field experiences served to temper the most speculative flights of the entomologists, radar "scientists" and meteorologists. At the same time we tried to encourage speculation where concrete evidence did not preclude various lines of research. As the Workshop progressed the participants began to recognize explicitly that our limitation in the understanding of insect flight should not subconsciously translate to a limitation in the flight itself and that the Icarian wings of insects might only exist to a nearsighted observer.

Early during the first day of the working sessions the pest management group reached an impasse. So little is known of insects in flight that pest management strategies are difficult to devise that might use radar in a tactical situation. Most ideas of the group participants were, in fact, for research rather than for direct pest management. Since the research group was to investigate most such ideas, the pest management group was left primarily to broad speculation with subsequent recommendations that programs be conducted to define more fully where radar may be useful.

These proceedings contain the formal papers presented the first day, along with the product of the working groups. We have summarized the recommendations of the groups, since many of the individual group recommendations are redundant. We intend this document to be useful to NASA and the USDA for assessing their current radar entomology programs, and to entomologists in general for formulating future programs that could benefit from this new application of radar technology.

We would like to thank everyone who unselfishly gave valuable time to explore an idea whose time is only slowly coming and, hence, might not be of immediate use to them. And lastly we thank Gail Rogers and Helen Shirk; two highly competent secretaries who provided continuous service to the workshop.

WORKSHOP PURPOSE

General: To familiarize insect population ecologists, pest management scientists, meteorologists and radar scientists with each other's disciplines in such a way that (a) radar scientists can formulate systems specifications for a dedicated insect observing radar, (b) research meteorologists can formulate approaches to using radar to correlate atmospheric phenomena with insect movements, and (c) insect population ecologists and pest managers can appreciate various radar capabilities and begin to formulate problem solutions in terms of these observing techniques.

Specific: To produce a document that represents a consensus - with dissenting views, where necessary - of:

   (a)   the potential role of radar in insect ecology studies and pest management.

   (b)   the potential role of radar in correlating atmospheric phenomena with insect movement.

   (c)   the present and future radar systems realistically possible for use in insect ecology and pest management.

   (d)   program objectives required to adapt radar to insect ecology studies and pest management.

   (e)   the specific action items required to achieve the objectives stated in part (d).

PRESENTED PAPERS.

The Role of Insect Dispersal and Migration in

Population Processes

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My assignment is to present a general discussion of movement as it functions in the population dynamics of insects, in a manner of interest to the non-biologists as well as the biologists in this audience. This is a difficult task, for my past attempts to hit two targets with the same arrow have usually resulted in clean misses of both. I must add still another escape-clause, before throwing caution aside, in speaking on a topic undoubtedly better understood by some members of this workshop. I accepted this assignment with the clear understanding that lead time was inadequate for the preparation of a scholarly paper of significant heuristic value to ecologists and entomologists. However, in spite of these qualifications, I was pleased to receive an invitation to participate in this workshop, which I hope will stimulate productive research on a topic of great basic and applied scientific importance.

Insect movement is far too complex, biologically significant and variable to discuss holistically in the allotted time. Thus, I should first like to narrow my topic and place my views within the context of some other approaches to the topic. Movement may be studied from many perspectives, including the following:

1. Morphological – physiological: - structure and function of skeleton, muscles, nerves and endocrine system relative to locomotion.

2. Behavioral: – mobility, vagility and agility in terms of stimulus-response of various levels of complexity (i.e., reflexes, kineses, taxes, transverse orientations) including an analysis of consistency and variation.

3. Ontological: – how movement serves the needs of individuals in obtaining requisites and protection during their life cycles.

4. Ecological: – roles of movement in population processes (i.e., how does movement function in relation to variations in temporal and spatial patterns of insect populations and environmental heterogeneity).

5. Evolutionary: – how and why derived. Integrates all perspectives.

Those studying movement from any one of these (or other) approaches may concentrate their attention exclusively to a single species, a group of species defined on the basis of similarities (e.g., taxonomic, behavior, ecological, etc.) or use a very broad comparative approach in the search of broad generalizations and causal theories. Most studies are aimed at description, prediction, and understanding in varying combinations.

An approach to movement exclusively from any one of the above-mentioned (or other) views runs the risk of unnecessarily narrow assumptions, which often lead to faulty conclusions. I run this risk today, because my approach is primarily ecological and evolutionary, biased toward Lepidoptera, and will be more conceptual than substantial. My main emphasis will be on the description, prediction and understanding of wide-area spatial and temporal patterns of Lepidoptera.

I shall briefly address the following topics: (1) terminology; (2) movement from a population view; and (3) describing, predicting and understanding population patterns, including some evolutionary considerations.

I shall not present a review of relevant literature nor attempt to acknowledge sources of information and ideas. Thus, I cannot claim originality for any useful views expressed but must be responsible for naive and misleading interpretations. I have terminated the paper with a list of the references which have served as my chief entree to published information on insect movement.

TERMINOLOGY

Modes of movement: One finds many modes of travel among the million-odd species of insects. Walking, crawling, hopping, and swimming may occur in larval and adult stages, whereas flying is limited to adults of winged species. The movement resulting from these intrinsic modes is often modified by extrinsic factors, and certain species have evolved morphological and behavioral mechanisms which in essence take advantage of extrinsic forces for their transportation. For example, many species are phoretic, hitch-hiking on other organisms, and other species have evolved life styles compatible with being swept along, aloft and away on currents of water or wind. Thus movement at times is active (under at least partial intrinsic control) and at other times passive (largely under extrinsic control). When the timing, duration, direction and distance of movement are essentially the result of extrinsic forces, it is said to be accidental and the insects involved classified as vagrants. Most long-distance (relative to intrinsic mobility of the species) movement involves both intrinsic and extrinsic control.

Some attempts to categorize different kinds of movement: Some exceptionally knowledgeable scientists will and others will not agree with the following interpretations, since movement terminology continues to be vague if not controversial.

Movement that results in noticeable changes in spatial relationships (distances between individuals) is dispersal. Dispersal is in essence a scattering, and results in interspersion when within the breeding habitat and when outside the breeding habitat, migration.

Interspersion is the result of so-called trivial movements during periods when the individuals involved respond readily to local (vegetative of Kennedy 1961) stimuli (i.e., mates, oviposition sites, food, shelter appropriate to a breeding habitat).

Migratory movements remove the individual from the breeding habitat of its origin during periods when it does not respond normally to local stimuli. In many species, this occurs shortly after adult eclosion. Where active flight is involved, it is often above the boundary layer (i.e., a height where wind speed equals flight speed).

It is difficult to draw a clear distinction between trivial and migratory movement. Hence, the usefulness of the terminology is impaired. A part of the difficulty lies in the problem of defining the breeding habitat spatially and temporally, and, hopefully, such will become easier with the development of better technology for monitoring movement. Another difficulty lies in the evolutionary interpretations of dispersal, which I shall discuss briefly in a subsequent section.

These various views of movement merely set the stage for studying its ecological significance, because studies too narrowly restricted to movement cannot answer significant questions regarding species population performance.

MOVEMENT FROM A POPULATION VIEW

The roles of movement in population performance can be understood only when viewed within a holistic study of a population's life system, as simplistically represented in Figure 1.

The life system is composed of two types of factors: those intrinsic to the population and those extrinsic to it. There is a constant inter-action between these two types of factors, and among factors of the same type, through various interactive processes and self-regulating mechanisms. The chief categories of interactive processes are natality, mortality, dormancy and movement and each is a composite of many subprocesses. For example:

Natality – defined very broadly to include egg laying, embryonic and post-embryonic development up to the reproductive adult stage.

Mortality – death at various ages and by many different agents and processes, such as desiccation, drowning, predation, parasitism, disease, accident, etc.

Dormancy – temporary cessation of activity of many types including aestivation or hibernation and quiescence or diapause.

Movement – different types as described earlier.

These major processes through which the individuals of the population interact with their extrinsic environment are themselves interactive. For example, movement has many functions relative to natality, mortality and dormancy.

The interactions among individuals of the population are also of importance to the regulation of the population as a whole and are indicated in the figure by the term "self-regulatory mechanisms". Such mechanisms vary widely from primitive scramble type competition and cannibalism to very advanced adaptations for controlling reproduction and microhabitats, as exemplified among social insects. The lepidopterous insects of most interest in the context of this workshop are thought to have only very primitive self-regulatory mechanisms, but this tentative conclusion should be viewed with caution. Perhaps density-related movement into a heterogenous environment is importantly involved in regulation and gene flow.

Figure 1 depicts a continual change in both the target population and its effective environment, with the entire system being driven by solar energy in the form of weather and, at least temporarily by man, who presently is inserting huge energy subsidies (chiefly fossil fuels) into the life systems of the insects of central interest to us. Thus, both the target population and its effective environment are open-ended interacting systems, the former subject to organic evolution and the latter to both organic and cultural evolution. Thus, if one of our goals in studying movement as it relates to population processes is to predict more accurately, we must face the fact that we are not dealing with deterministic systems and our predictions will be probabilistic.

What specifically do we wish to predict? From the view of basic population biology, we wish to predict the performance, in terms of numbers and quality in space and time, of a population possessing defined intrinsic attributes in an effective environment possessing defined characteristics. From the view of applied population biology, we wish to predict population performance under various optional manipulations of this effective environment. These two views can be clarified by reference to two figures (1 and 2) used in a previous paper (Rabb 1978), which I quote as follows:

With reference to Figure 1 of Rabb (1978): - "In any one geographical area we wish to explain changes in population size and quality from time to time (the temporal curve) and place to place (the island-like representation of spatial pattern). Also very importantly, we wish to understand processes which limit the rise and fall of numbers and regulate the population around a mean level (the horizontal line). Additionally, we are interested in differences between two geographical areas which result in different mean levels of abundance of the same species (that is, the contrast between A and B)."

With reference to Figure 2 of Rabb (1978): - The principal objective of applied population biology of pest species is to apply understanding of population biology in two general ways. "The first objective is to lower mean levels of insect populations, when and where they are pests by using preventive tactics, or to effectively raise the economic injury threshold

(for example, by employing a pest-tolerant crop variety). The second general objective is to use remedial procedures to temporarily suppress populations when and where they exceed thresholds."

DESCRIBING, PREDICTING AND UNDERSTANDING POPULATION PATTERNS

Population patterns must be described accurately before it is possible to develop and test a system to predict population consistencies and changes and before cause and effect relationships can be elucidated in the search ·for understanding. Perhaps one of the greatest limitations in population studies is the inadequate attention given to the accurate description of the population to be studied. The spatial and temporal constraints· arbitrarily placed on the study will, in large measure, determine the potentiality of the study to answer specific questions about the population's performance. In the case of many species of highly mobile Lepidoptera, populations as defined for study have been typically too small in spatial dimensions and too short in time span to contribute appreciably to a predictive understanding of population performance.

Spatial dimensions: With the caution that space and time are inseparable, how do we arbitrarily set spatial limits on populations? A hypothetical wide-area species population is depicted in Figure 2. It can be studied holistically (A), or in deme units (B), or in intrademe units (C).

For very accurate prediction, the study area should be large enough to encompass a self-perpetuating population isolated from all other populations with which it is capable of exchanging genetic materials. Obviously, such a study area must be very large for mobile Lepidoptera, but we don't know just how large it should be for noctuid pests in the southeastern U.S.A. It may be necessary to address the entire species population if there is evidence of very significant long-distance displacement and no clearly distinguishable demes. On the other hand, where demes can be identified, studies of them may yield highly predictive capability if performance criteria are affected only by intrademe movements or if there is an accurate monitoring of movement in (immigration) and movement out (emigration). Defining populations as intrademe units (as in C of Figure 2) greatly restricts the potentiality of developing predictive capability. However, such studies can be useful in studying performance criteria affected principally by trivial movement and not by long-distance displacement. However, it is risky to generalize to other intrademe units or demes on the basis of information in one intrademe unit or a deme.

Temporal dimensions: The population will have to be studied over many years if a high level of population pattern predictability (months or years into the future) is desired. Information essential to prediction on the population and its effective environment must be organized as a conceptual model. There is now strong support for the notion that these conceptual models should be refined and transformed into mathematical models of the population's life system – models suitable for mathematical and/or simulation analyses. If short-term prediction is all that is·desired, these models can

be constructed largely on the basis of information correlating population behavior with the increase or decrease of observed environmental factors (for example: temperature, rainfall, a cultural practice, natural enemy populations, etc.). However, if it is desired to understand population behavior to the extent that one can predict the effects of proposed environmental manipulations on the population, the models must more accurately reflect cause and effect relationships and interactions. While conceptual and mathematical models enhance the scientific method when used properly, they alone cannot be relied on in predicting future events, except for very short projections into the future and under very special circumstances. This rather disturbing conclusion is inevitable because of the open-endedness of both the population and environmental systems involved. Some researchers may not like to admit this uncomfortable fact to those responsible for funding research because the latter in so many cases want absolute answers when such can not be given. Thus for continual maintenance of a high level of predictability (even for relatively short-range predictions) the population will have to be studied into the indefinite future. In addition, a component of such studies must be an effective biological monitoring system supplying key information on the population and its effective environment, including weather, food resources and more important enemies. The more holistic and refined the model, the less biological monitoring necessary, but the need for the latter can never be eliminated if reasonable levels of predictability are to be maintained. We would not even consider sending a rocket to the moon without some ability to monitor its movement and make corrections from time to time based on this monitoring. How then could we hope to predict the status of complex biological systems without monitoring capabilities.

When dealing with cyclic species or highly fluctuating populations, such must be studied through enough years to identify factors responsible for cyclicity and fluctuations, and to develop and test hypotheses as to how factors influence the population performance. To paraphrase, if expertise is to be developed to predict when and where outbreaks are to occur, the populations must be studied during the endemic as well as the epidemic stages. (Unfortunately, those supplying money for research lose interest in studies during endemic periods. Consequently our knowledge of dynamics during endemic periods is extremely weak, as is our ability to predict with accuracy. A parallel case is research on rare species, which could add much to our understanding of population biology. Obviously, problems of sampling make research on endemic populations and rare species very costly, but in terms of potential benefits the costs seem justified.) Of course, correlation and regression analysis involving suspected environmental factors which may be causing changes - such as key-factor analyses - may be helpful initially, but a sound basis for confident prediction will require hypotheses formulation and testing involving experimental procedures, and such will require long-term field studies of populations if conclusions are to be validated.

How shall we study the noctuids of agricultural importance in southeastern U.S.A.?: There are at least seven noctuid species (fall and beet armyworm, corn earworm, tobacco budworm, cabbage and soybean looper, and velvet bean caterpillar) of great interest in the southeastern states,

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and though we have some information on their spatial and temporal patterns, this information is inadequate for reasonably accurate predictions. Movement certainly plays very significant roles in their survival strategies, because all are highly mobile.

As a point of departure, perhaps it might be useful to suggest some possible types of wide-area population patterns and the possible significance of certain factors which might be responsible for them. Though redundant, it is critically important to view these patterns from the "field" perspective, since they are dynamic in space and time.

Three possible patterns are simplistically depicted in Figure 3, in which each rectangular area represents the range of a hypothetical species population and each dot represents a site occupied by successfully reproducing adults. The temporal dimension for each pattern is represented by four successive time periods at 3-month intervals, from January to January.

Figure 3A represents one possible dynamic pattern – the waxing and waning of populations from permanent foci when there is little directional long-distance displacement and the waxing is into areas of only temporary favorability.

The ebb and flow pattern (Figure 3B) which results from great long-distance, net directional expansion also entails expansion into areas of temporary favorability and contraction to favorable refuges.

When an entire population moves from place to place, its pattern may resemble Figure 3C. While Figure 3 was conceptualized as very wide-area patterns of highly mobile species, these patterns probably can be seen in the seasonal movements of relatively immobile species. For example, the movements of entire colonies of certain species of social Hymenoptera from site to site may present a nomadic pattern.

Perhaps none of the noctuid species mentioned earlier display seasonal population patterns as presented in Figure 3. Certainly, patterns of many species seem to be a mixture of the types shown. However, the important point to make is that the information in hand is insufficient to characterize accurately the patterns of the species of interest. If we are to develop better predictive methods we must (1) organize a more effective regional research effort and (2) develop and use technology for measuring adult movement more appropriately.

Broad population patterns should be reflective of survival strategies, which *in toto* should be somewhat different for each noctuid species (in keeping with the "unique" criterion of most species definitions). Conversely, it seems logical that if one understood the similarities and differences among species in their survival strategies, he (or she) would then understand the similarities and differences in their population patterns resulting from convergent and divergent evolution. Some of our greatest strides in understanding have resulted from scientists who have used this approach. Wellington (1977), for example, advocates developing a zoocentric view of the world in research on insects – in an attempt to see

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the heterogeneous environment from a particular insect's (or insect species') view. Greater attention to those that survive should lead to more rapid progress in understanding population dynamics and genetics.

The intellectual exercise of placing species on a continuum between extreme r- and K-strategists is challenging, heuristic and perhaps is a useful point of departure in studying population patterns (see Southwood 1977 for one of many treatments). However, species survive because of a very large complex of adaptations (and luck), and today we are interested in how movements might be adaptive or non-adaptive .

The evolutionary premise is that intrinsic modes of movement have been selected because of their survival value, hence are adaptive. Thus, there, is no problem in accepting trivial movements (as defined above) as adaptive.

On the other hand, due to dispersal (including movement due to innate characteristics as well as accidental transport), populations expand into ·sub-marginal, marginal and intolerable areas during reproductive periods (Huffaker and Messenger 1964). Under such conditions, some lineages evolve high mobility and tend to become migratory and/or nomadic, escaping intolerable local conditions through movement. Other lineages evolve dormancy mechanisms and survive intolerable conditions *in situ* until favorable conditions return.

Three of the hypotheses advanced. to explain various dispersal patterns of insects as adaptive are that they provide a means of (1) eliminating excess populations, (2) escaping natural enemies, (3) keeping pace with changes in location of habitats. I have not reviewed this subject adequately, but Southwood (1962) gives an entree to the older literature and presents his own interpretations including the conclusion that the most basic evolutionary explanation for adaptive migration "lies in its enabling a species to keep pace with changes in location of its habitats". He also notes a positive correlation between the level of migratory movement of species and the impermanence of their habitats, giving many examples among the arthropods.

From the view of the species, dispersal results in colonization of new habitats and, at least in some cases, the abandonment of unsuitable habitats. In the process, population pressures may be relieved, enemies may be escaped, and mortality from intolerable physical factors may be avoided. One might logically expect differential effects of these latter factors in both the evolution and population dynamics of a species to be different for each species. Thus, the limitations of our broad generalizations should be kept in mind as we use them to guide our attention to a succession of factors giving a finer and finer tuning of population performance.

It seems instructive to consider the possible effects of man's environmental manipulations on the evolutionary pathways and resulting population patterns. The development of agriculture during the past several hundred years in southeastern U.S. has resulted in an extremely large environmental arena which is in large measure artificial, i.e., kept strikingly different,

by use of fossil fuel energy, from the environment in which most of the component organisms evolved. Man's continual, but changing, use of energy and materials in maintaining and modifying agroecosystem structure has had differential effects on the organisms involved and some of these most favored by the artificiality imposed on nature have by our definition become pests, such as the noctuids mentioned.

Nature is a ruthless book balancer. If a species evolves with say a fecundity of 100 viable eggs per parental pair, 98 of them must on an average perish, and much of the 98 percent loss can be due to dispersal into a heterogeneous environment in which risk of death is at times and places very high.

Risk from dispersal losses varies from spring to fall for multivoltine species and is greater for individuals of late summer generations developing in temporarily favorable habitats far from suitable overwintering conditions. Agricultural practices have expanded these temporarily favorable habitats, for some species, far into areas climatically unsuitable for winter survival. The penetration into these intolerable zones (i.e., intolerable for permanent residency) is particularly deep for multivoltine, highly mobile species such as many of our noctuids. This is true because that part of dispersal losses of spring and summer generations, once due to lack of appropriate food, has been reduced by man's alteration of naturally evolved plant communities and wider provision of suitable temporary breeding habitats. If such is true, then man's agricultural practices have in effect led large streams of insect biomass into dead ends. This "pied piper" effect seems to "pervert" the survival strategies of the species involved, at least from an ecosystem efficiency perspective.

While my perspective herein is largely from the view of wide-area patterns, I think it pertinent to note that man's cropping systems also influence the finer ramifications of biomass flow within very local areas and that the "pied piper" effect can be in relation to destroying synchrony (spatial and temporal) between parasite and host as well as leading biomass into disastrous physical conditions. (For example, in the large acreages of tobacco in North Carolina, significant biomass of Manduca sexta is produced each year. As the season progresses, parasitism of M. sexta by Apanteles congregatus increases and becomes extremely high prior to winter. Both M. sexta and A. congregatus exhibit diapause and hence are well protected from severe winter conditions. However, the emergence of the two species in the spring is not synchronized, A. congregatus emerging approximately one month before M. sexta. Hence spring emerging A. congregatus perish if they do not find suitable hosts other than M. sexta for their first generation. These other hosts are various species of Sphingids which are often not available or in very low numbers adjacent to tobacco fields in the much simplified agroecosystem. Thus, these "tobacco-produced" A. congregatus seem to be dead ends too.

In presenting this view of the possible effects of agricultural practices in "perverting" survival strategies, there is no intention to ignore genetic plasticity of insect populations and the organisms with which these populations interact. However, man in a very short time (geological) has greatly altered the communities and ecosystems in which the

indigenous and introduced species have coevolved, by many different inputs of energy and materials, each affecting different species differently. Genetic response of populations has been extremely variable. On the other hand, some types of adaptations (resistance to pesticides or plant toxins, for example) arise rather quickly. On the other hand, man's cropping practices present certain challenges (the "pied-piper" effect) for which efficient adaptations have not evolved. Perhaps much longer time periods are required for adaptations of population and community systems leading to increased efficiency (consumption : production). And too, such would require coevolution with interacting species which man often short-circuits by genetic control of crops and by changes in his use of energy and materials.

While it may be interesting to speculate as I have done, on the factors responsible for population performance now and in the future, the testing of hypotheses cannot proceed satisfactorily until we describe dynamic population patterns more accurately than we have done in the past. Hopefully, radar will be another useful technique. However, we now have many techniques which we are not using as effectively as we might within the context of a well-conceived plan of research on population performance. The principal reason for this unfortunate state is our inability to work together effectively over wide areas within the context of the various institutions, agencies and other political structures which must be involved. A fine new technique will not remove this more fundamental roadblock. If we are in fact to use ecological principles fully for improving pest management, such constraints must be removed.

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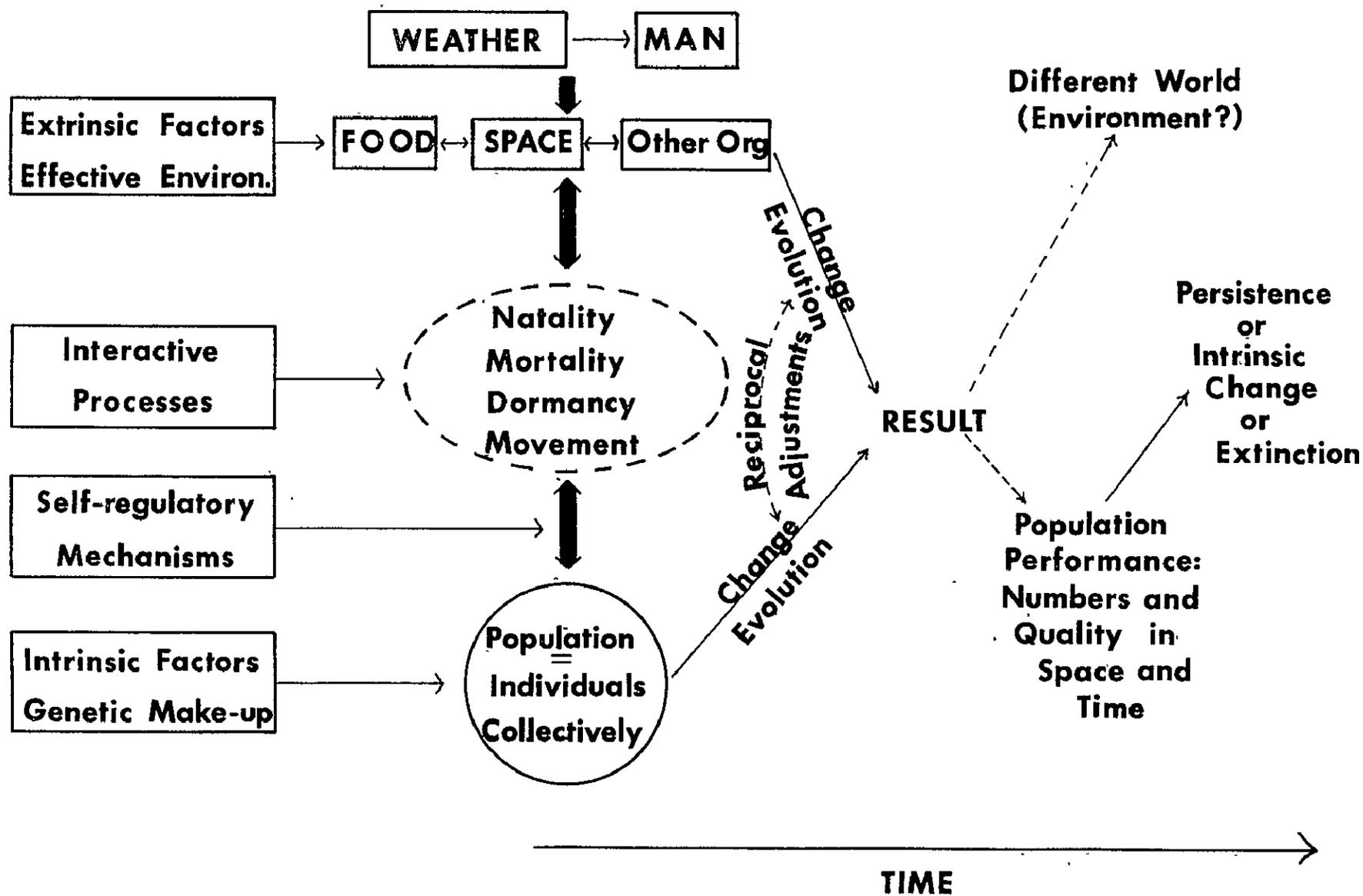
Figure 1. Generalized representation of a life system concept presented as a point of departure in studying the role of movement in the performance of an insect population.
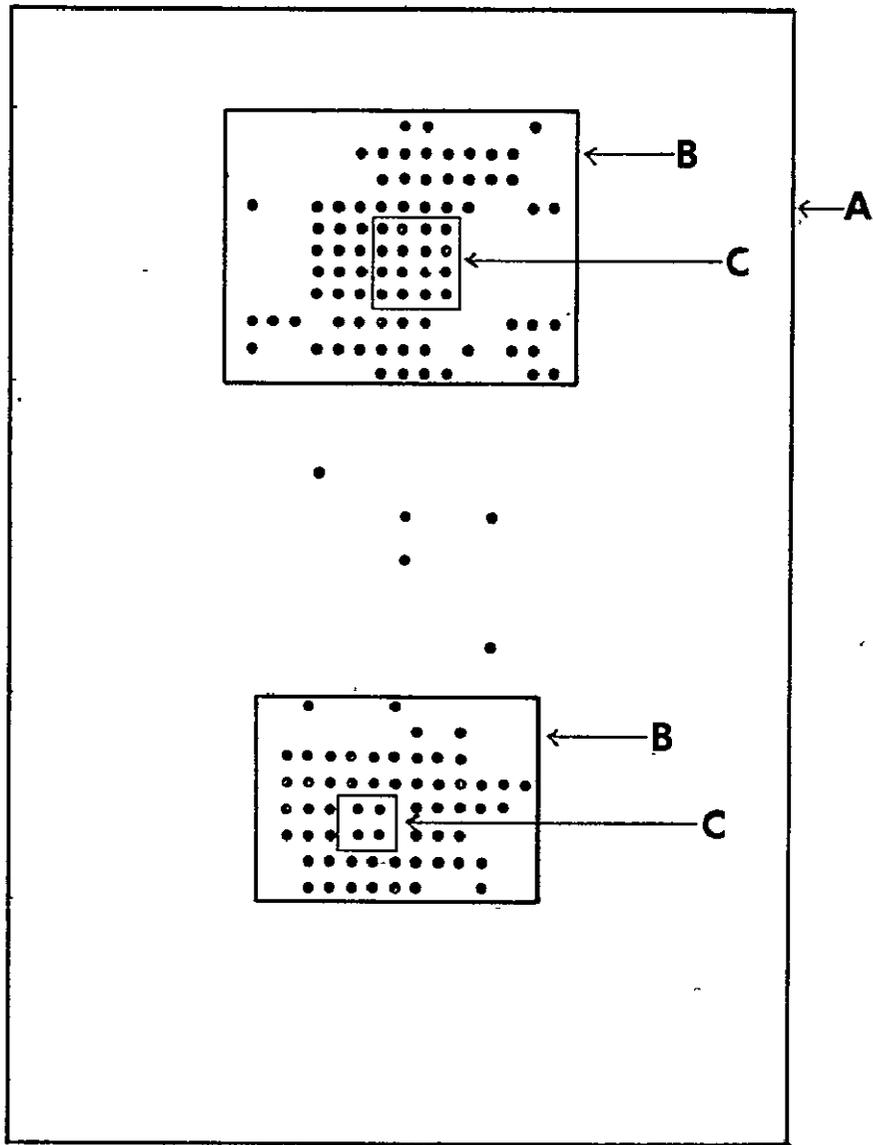
Figure 2. Diagrammatical representation of the species range of a
hypothetical insect at a point in time during the breeding
season illustrating three types of populations targeted for
study: A - the entire species population; B - partially
isolated demes; and C - intrademe units. Each dot
represents a site occupied by a breeding population of the
species.

A - Waxing and Waning of Permanent Foci (Little directional long-distance displacement)
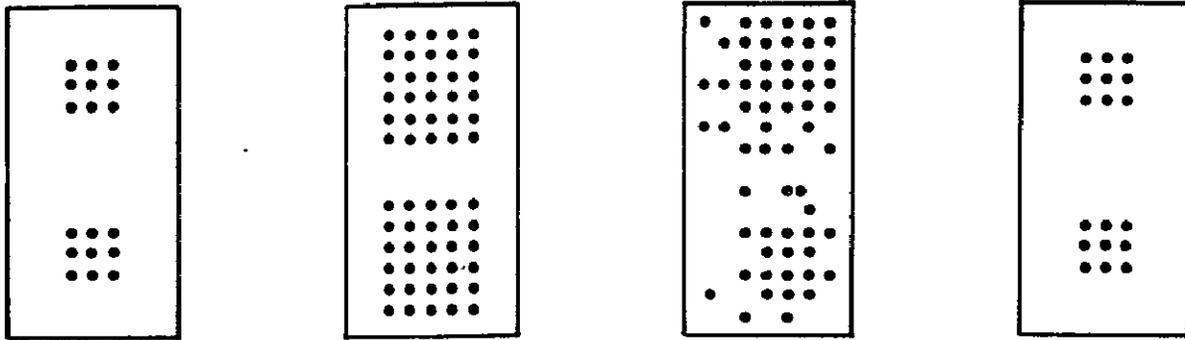
B - Ebb and Flow (Great long-distance, net directional expansion)
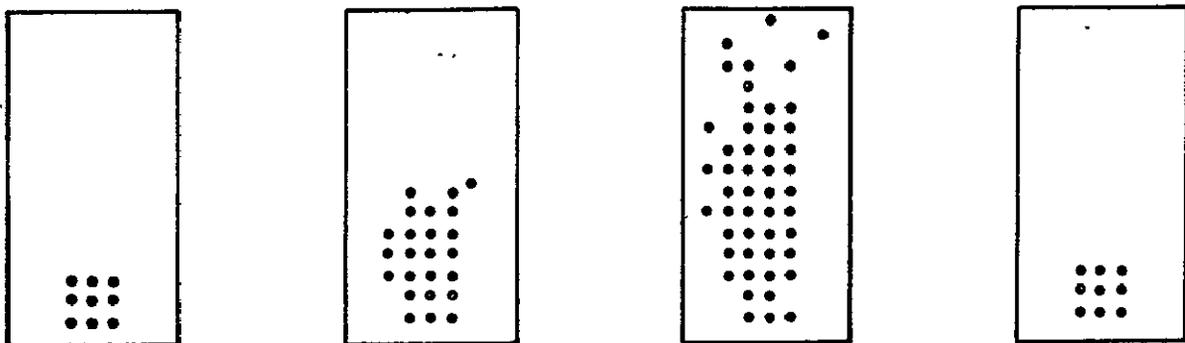
C - Nomadic Movement (Great long-distance displacement)
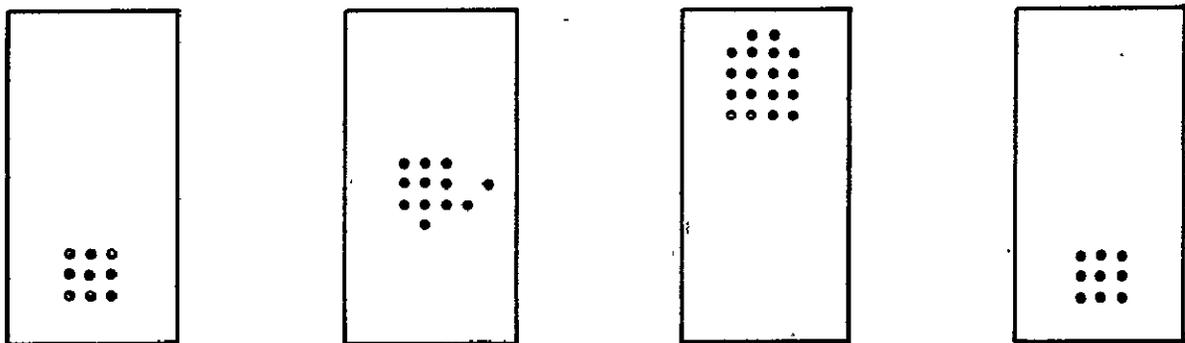
← 1 YEAR →

Figure 3. Three hypothetical types of seasonal patterns of insect populations: A — wax and wane of permanent foci - little directional, long-distance displacement; B - ebb and flow - great long-distance, directional displacement, and C - nomadic movement - great long-distance, displacement. Each rectangle represents a species range and each dot a site in which reproductive adults are found.

SHORT-RANGE MOVEMENT OF MAJOR AGRICULTURAL PESTS

by

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Many insect species which infest annual crops must regularly disperse if their continued survival is to be assured. A knowledge of the time, magnitude, and causes of dispersion of both major pests and beneficial insect species would greatly aid in pest management programs. Where adequate knowledge of insect pest dispersion exists, significant improvements in pest control practices have often resulted and the control practices are more holistic in scope.

There are numerous techniques to assess short-range movement of major agricultural pests. The most commonly used technique is visual observations of population fluctuation which cannot be accounted for by either mortality or natality. An example of where this technique was used to study short-range dispersion of a major agricultural pest and the eventual suppression of the pest, is lygus bugs in the westside of the San Joaquin Valley of California.

Lygus bugs are a major pest of cotton in California (Stern, 1973). In early spring Lygus moves from the drying foothill plants into the safflower crop, which is the only available host crop. Since safflower is rarely treated with insecticides, it acts as a major breeding habitat for Lygus. The lygus bugs complete one generation in safflower and populations can reach extremely high levels. By mid-June, the safflower crop begins to mature and dry, and the lygus bugs move to the surrounding young cotton fields (Mueller and Stern, 1974). Since the movement from safflower to cotton is protracted over many weeks, numerous insecticide treatments must be applied to the cotton to prevent damage by the Lygus. However, a single well-timed insecticide treatment applied to the safflower just prior to crop drying would break the cyclic dispersal pattern of Lygus, and thus, prevent repeated insecticide applications to cotton (Sevacherian, et al., 1977). This control practice which was initiated in 1970 has gained wide acceptance by California growers and has resulted in a significant reduction in total insecticide usage.

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Other techniques to assess short-range movement of insect pests have used various markers such as paints, dyes, fluorescent dusts, radioactive isotopes, and rare metals. These techniques have an advantage over direct observations since a known number of marked insects can be released at a known location and the movement of these marked insects can be followed over time and space. An example of where this technique was used to study the movement of a major agricultural pest is lygus bugs in the south and east sides of the San Joaquin Valley.

In these regions of the Valley, there are large acreages of alfalfa hay and cotton while little safflower is grown. Lygus bugs can increase to high numbers in alfalfa hay where they cause little or no economic damage. However, when the hay fields are harvested, Lygus adults often move to adjacent cotton fields (Sevacherian and Stern, 1975) Thus, many insecticide treatments must be applied to cotton fields which are adjacent to alfalfa hay fields.

However, if Lygus is given a choice between alfalfa and cotton, Lygus prefers alfalfa. Thus, a large number of adult Lygus were collected in alfalfa hay fields by a suction device and marked with a fluorescent dust (Stern and Mueller, 1968). These marked adults were then released in cotton fields and they immediately moved back to the alfalfa fields; whereas marked adults released in alfalfa fields tended to remain there (Sevacherian and Stern, 1975). From the observed dispersal capability and host plant preference of lygus bugs, developed the idea of strip harvesting of the alfalfa hay fields.

In the strip harvesting technique, an alfalfa field is harvested in alternate strips (200-300 ft) so that two different stages of hay growth are present in the field simultaneously. The alternate strips are harvested at approximately 2-week intervals. When one set of strips is harvested, the alternate strips are about half grown, and thus the field is never completely bare of standing hay. The field becomes a more stable environment, and the Lygus moves from the harvested strips to the half-grown instead of leaving the field and invading adjacent cotton fields (Stern, *et al.*, 1967).

This technique of Lygus control has not been accepted by the growers because of irrigation and harvesting difficulties. However, a modification of the technique is widely used throughout the San Joaquin Valley. Growers have divided their large hay fields (160 to 320 acres) into a number of smaller fields. The growers then harvest these smaller fields alternately and, thus, herd the adult Lygus between them in much the same manner as the strip harvesting technique.

With the implementation of these two control techniques (i.e., safflower treatment and alternate block harvesting of alfalfa) which resulted from a knowledge to Lygus dispersal, lygus bugs have been relegated from the major or key pest of cotton to an occasional pest. The insecticide burden on cotton throughout the San Joaquin Valley has been significantly reduced. Prior to the establishment of these programs, it was common-

place to apply from 6 to 8 insecticide applications to cotton for <u>Lygus</u> control. In 1976, the total number of insecticide applications had been reduced to 1 or 2 and these treatments were usually applied for spider mite control. With this low insecticide usage on cotton, secondary pests such as cotton bollworm, cabbage looper, and beet armyworm are rarely a problem (Van Steenwyk, <i>et al.</i>, 1975).

Now I want to turn to a new technique to assess short-range movement of a major agricultural pest. The technique eliminates many of the assumptions and problems associated with direct marking techniques. In this technique, the host plant on which the pest insects feed is marked with rubidium. Rubidium is an alkaline earth metal. It is nonradioactive and has chemical properties similar to those of potassium. Rb will freely replace potassium in the cell metabolism of both plants and insects. Of equal importance, is the low natural abundance of rubidium in the environment which is usually below 5 ppm Rb^+. Thus, insects which feed on rubidium plants become labelled by the ingestion of marked plant tissue or fluids. The movement of these marked insects can be assessed by capturing specimens at various distances and directions from the treated plants and, if their rubidium content has been significantly increased over background levels, then that insect developed on the treated plants (Berry, <i>et al.</i>, 1972).

The advantage of this technique is that the insects are not manually captured, marked, or released. Thus, there is no modification of their normal behavior. These types of studies were first conducted using radioactive phosphorus (P_{32}) (Pendleton and Grundmann, 1954). However, recent State regulations have banned most field work with P_{32} in California. Thus, rubidium must be developed as a substitute for P_{32} if work in this line is to be continued.

An example of where this technique was used to study the short-range movement of a major agricultural pest is the pink bollworm in the south desert valleys of California. Pink bollworm is the major or key pest of cotton in southern California and Arizona, and it dominates the pest control practices in these regions. Pink bollworm is also a potential threat to cotton production in the San Joaquin Valley, and there is an extensive effort by the California State Department of Agriculture and the U.S. Department of Agriculture to prevent its spread through the release of sterile pink bollworm moths into the valley. However, a large number of native male pink bollworm have been captured in the San Joaquin Valley over the past 8 years.

The short-range movement of pink bollworm was studied by treating a cotton field with rubidium during a 2-year period. Adult males and females were captured at various distances and directions outside of the treated fields. These adult pink bollworm were analyzed for their rubidium content by atomic absorption spectrophotometry. Any adult that contained significantly high rubidium level over background levels was considered to have developed on the treated plants (Van Steenwyk, et al., 1978a). It was found from these studies that pink bollworm departed the fields to a much greater

degree in September and early October then either August or late October, although the marked field population was large during the entire period. It was also observed that the time and magnitude of the dispersal differed for each sex. Females depart the fields about 2 weeks before the males and at a much reduced rate. The movement out of the fields for both females and males was apparently triggered by a change in the physiological state of the cotton plant in which the larvae develop (Van Steenwyk, *et al.* 1978b).

How does the above information relate to the sterile moth release program in the San Joaquin Valley of California? The number of native moths captured in the San Joaquin Valley would be expected to substantially increase during September and October and the release program should be started to combat this influx of moths, and if a summer storm occurs during this period as has happened during the past two seasons, an extremely large moth catch should be expected.

In conclusion, a knowledge of the short-range movement of major agricultural pests is an essential prerequisite to the development of sound pest management programs. Unfortunately, the dispersal of most major agricultural pests is one of the less known facets of their biology. Thus, for pest management programs to advance in the future, greater emphasis must be placed on a better understanding of insect movement.

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SELECTED EXAMPLES OF DISPERSAL OF ARTHROPODS ASSOCIATED WITH

AGRICULTURAL CROP AND ANIMAL PRODUCTION

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The fact that many insect species, both beneficial and pest species, move short distances in expanding their habitat and/or travel long distances during their lifetime to new or similar habitats is well documented (Williams 1957, Schneider 1962, Johnson 1966, and Johnson 1969).

From an entomologist's point of view, movement of insect pests and beneficial species are of particular importance to protection of crops and animals, and thus may have significant impact on crop and pest management systems. Each species appears to exhibit unique and characteristic behavior in making these movements. Also, the factors influencing movement vary with each species and may involve a broad spectrum of ecological, biological, and physical stimuli.

There are many examples of arthropods associated with cultivated crop production that exhibit characteristic movements into and away from crops and/or areas of animal hosts. This presentation is not intended to be an exhaustive or complete review of these records but rather a selection of a few examples of insect species exhibiting such dispersal and its practical significance to crop and/or animal protection entomology.

Screwworm, Cochliomyia hominivorax (Coquerel)

The screwworm is an obligatory parasite of warm-blooded animals. It is primarily a pest of domestic animals and wildlife; however, man is susceptible to attack under certain circumstances. Uncontrolled, the screwworm causes losses of millions of dollars to the livestock industry. The insect is restricted to tropical and subtropical areas in the winter months but migrates hundreds of miles from its overwintering areas during other times of the year (Barrett 1937). Hightower et al. (1965), from recapture records

of reared and irradiated released screwworm flies, found that individual screwworms

dispersed 180 miles from release points in less than 2 weeks but disappeared from

invaded areas with temperate climate in winter months. This interaction of screwworm

migration and temperature was an important contributing factor in developing the strat-

egies that led to the successful demonstration of the sterility method of insect control

(Knipling 1955), one of the outstanding achievements in modern entomology.

In the Southeastern eradication program, the identification of yearly migration of

populations from southern Florida focused attention on the fact that during the winter

months the habitat of the insect was reduced to less than one-half the size of the habi-

tat during the warmer months of the year. Thus, control pressure could be intensified

at the source of the population. Further, the "barrier" concept was formulated whereby

sterile screwworm flies were released in a 200-mile-wide area of northern Florida and

southern Georgia to prevent migration into Georgia and other southeastern states. This

concept of a barrier was particularly important and was later one of the reasons the

sterile release method for screwworm control could be successfully applied in the south-

western United States.

<center>Pink Bollworm, <u>Pectinophora gossypiella</u> (Saunders)</center>

The pink bollworm, which is recognized throughout the world as one of the most

injurious pests of cotton, was first detected in the United States in Texas in 1917.

This initial infestation was eradicated as were infestations in ensuing years in

Louisiana, Arizona, Georgia, and Florida (though infestations in wild cotton still

exist in southern Florida). Then reinfestation (suspected moth migration from Mexico)

occurred in the lower Rio Grande Valley in 1936 that could not be contained, and the

insect gradually spread to surrounding areas. By the mid-1950's, all of the cotton-

growing areas in Texas, New Mexico, and Oklahoma were infested as were sections of

Arizona, Arkansas, and Louisiana. By 1966, all of the cotton-growing areas in Arizona

were infested, and the insect was found for the first time in southern California.

Thus, by 1967, most cotton produced west of Louisiana and Arkansas was infested except

that grown in the San Joaquin Valley of California (Spears 1968).

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mented (Ohlendorf 1926, McDonald and Loftin 1935, Noble 1969). In addition, migrating pink bollworm moths from overwintered larvae have been demonstrated to initiate infestations in cotton isolated 35 miles distant from the nearest source of infestation (Bariola *et al.* 1973). Evidence for migrating moths is largely based on relative distances from known sources of infestation. However, the fact that migration occurs and threatens further spread to the San Joaquin Valley influenced the initiation in 1968 of sterile pink bollworm releases in Kern County to prevent migrating insects from establishing an infestation in the area.

Native pink bollworm moths have been captured in the San Joaquin Valley in pheromone-baited traps each year since 1968. These are strongly suspected as being migrants from southern desert valley cotton-growing areas over 400 miles distant. No established infestation in cotton has been reported to date. Thus, the recognition of the migration potential of the insect and immediate and continued action via the sterile release program appears to have prevented the pink bollworm from infesting cotton in northern California.

Heliothis spp.

Two species, Heliothis zea (Boddie) and H. virescens (F.) are of particular economic importance in the production of several major crops in the United States. Snow *et al.* (1969) found that H. zea dispersed over the entire 84^2 mile island of St. Croix when released from a central point and for distances up to 10 miles. Similar dispersal characteristics for H. virescens were demonstrated by Hendricks *et al.* (1973). In addition, Haile *et al.* (1975) found that when both species were released on St. Croix, they traveled considerable distances over water to other islands in the area. Sparks (1972) reported that released H. zea will disperse at least 16 miles in one night and 45 miles over a period of 1-4 days.

In view of the economic importance of these species, the high cost of control, and the crop losses, it appears that an efficient pest management suppression system must be developed to control them. However, any plan for total population suppression must

consider dispersal of the target insect. It is, therefore, encouraging that Lingren et al. (1977) were able to demonstrate that artificial barriers could be established by releasing sterile virgin females of H. virescens. The released females intercepted and mated with 91% of the native males moving into the area and provided a barrier zone of ca. 1100 feet.

Lygus spp.

Lygus hesperus Knight is one of the major insect pests in Arizona and California where it attacks a wide variety of cultivated crops. Stern *et al.* (1967), in an extensive ecological study, established the intercrop movement of these insects during the year in the San Joaquin Valley of California. The insects overwinter in alfalfa, which is the principal host, but move to orchard cover crops or weeds when the alfalfa is cut. Then they move back to alfalfa when cover crops are plowed under and/or weeds dry up. Thus, by late spring, alfalfa again is the main source (safflower may also be a source in some situations) of the insect but by mid-June, when alfalfa is cut again, millions move into cotton where they do extensive damage and often must be controlled by applications of insecticide. The insect does little damage to alfalfa hay crops, and the authors demonstrated that by harvesting the alfalfa in alternate strips, Lygus moved from cut mature strips to half-grown alfalfa (previously cut) and only a few moved to cotton. Sampling techniques used to demonstrate these intercrop movements were visual observations, sweep nets, sticky traps, and similar limited and laborious methods.

Prior to these findings, Lygus control was almost completely dependent on insecticides. Such use of chemicals was costly, and early-season applications to cotton often created secondary pest problems such as cabbage looper, Trichoplusia ni (Hubner), bollworms, Heliothis spp., and other insects.

Aphids

The green peach aphid, Myzus persicae (Sulzer), causes direct feeding damage and is the principal vector of leaf roll virus of potatoes and/or the associated net necrosis of tubers. Female aphids move to peach or other Prunus spp. trees in the fall

and deposit overwintering eggs. Thus, three to 30-thousand eggs of the green peach

aphid may overwinter on a single peach tree (Powell 1966) depending on the fall popula-

tion of aphids and the tree size. Progeny from these overwintered eggs produce winged

migrant aphid forms that in spring move to volunteer potatoes (that often contain the

leaf roll virus) and thereafter to commercial potato fields. They may, therefore,

infect these plants. Awareness of this pattern of movement resulted in the concept of

early spring control of the aphids in April and May when the aphid population is con-

centrated in a restricted and comparatively small habitat.

Early spraying of all peach trees in a 500-square-mile area reduced winged aphid

catches in traps 60%, net necrosis in potato tubers from 11% to 3%, and chronic leaf

roll from 43% to 10% (Powell and Mondor 1976).

The green peach aphid in the Pacific Northwest is also the most important vector

of sugarbeet western yellows and beet yellows viruses, diseases that cause annual losses

of as much as 25 to 30% of the yield of sugarbeets (Wallis, 1967c).. Unfortunately,

sugarbeet western yellows, the most prevalent of the yellows diseases there, can be

harbored by 30 or more hosts other than beets that, therefore, serve as reservoirs of

the virus (Wallis 1967a). Although the green peach aphid overwinters primarily in the

egg stage on peach trees, small numbers of the summer forms overwinter and feed on

plants growing all year in protected places. Intensive ecological studies showed

that many of these overwintering hosts of the summer aphid forms were also alternate

hosts of sugarbeet western yellows virus (Wallis 1965, 1967b). In fact, warm spring-

fed drainage ditches in sugarbeet-growing areas near Toppenish, Washington, were found

to provide a micro-climate 20-50°F warmer than the surrounding environment in which

the weeds and the aphids could flourish throughout the year. Thus, though aphids from

eggs overwintered on peach trees are free of virus until they feed on diseased plants,

the summer aphid forms that overwinter on infected weeds carry the virus to young sugar-

beet plants when they migrate to them in the spring.

These findings on interplant movement stimulated studies to determine whether

eliminating overwintering populations of aphids and weed hosts from drainage ditches

would reduce viral infections in nearby sugarbeet fields. One 22- and one 30-square-

mile area southwest of Toppenish that contained 42 to 53 miles of drainage ditches was

the test area; a similar area 4 miles east served as a check. During January, February,

and March 1965-1967, before sugarbeets began growing and aphids began migrating, the

weeds in the drainage ditches in the test area were destroyed by burning. In 1966,

91% fewer aphids and 76% fewer diseased plants were found in the area where the ditches

were burned than in the unburned check areas; in 1967, 75% fewer diseased plants were

found in the burned area than in the unburned check area. The increased yield in the

test area was estimated at more than 2 tons per acre, and the cost of ditch burning per

acre of sugarbeets protected ranged from $2.20 to $6.85 and averaged $4.00 for the 3

years (Wallis 1968).

Boll Weevil

The boll weevil, Anthonomus grandis Boheman, was first recorded in the United

States in 1893 (Howard 1894) and is currently estimated to cause annual cotton losses

and costs of control of $250-275 million (Rainwater 1970). The insect moves from cotton

in the fall to suitable nearby hibernation sites where it overwinters in diapause.

Emergence in the spring is followed by movement back to cotton.

This movement and recognition of the relationship between overwintering diapause

and winter survival resulted in the development of the reproduction-diapause boll weevil

control concept. Adkisson et al. (1966) used the modified concept to achieve reduction

in potential overwinter boll weevil populations up to 99%. Further, a grower-sponsored

program in Texas reduced cost of in-season insect control ca. 98% after only two years

of operation.

Beneficial Insect Species

Many insect parasites and predators also move within and between wild and culti-

vated crop plants in association with their hosts. For example, Fye (1971) reported

that predator populations increased in grain sorghum on Biotype C of the greenbug,

Schizaphis graminum (Rondani), and migrated to cotton as the grain sorghum matured.

Bryan et al. (1976) discussed the interplant movement and host-parasite-predator

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relationships in southern Arizona.' Briefly, the authors indicated that a large segment
of the insect population overwintered in London rocket until it matured. Then it moved
to desert plants. In each case, aphids and other soft-bodied insects were the major
source of food. As the desert plants matured, the predators moved to wheat and barley
to 'feed on greenbugs. As small grains matured, predators moved to grain sorghum where
again they fed on aphids. When grain sorghum matured, predators moved to cotton. The
authors suggested that the manipulation of this sequence, in combination with other con-
trol measures, could provide highly efficient use of naturally occurring predators and
parasites for control of cotton insect pests.

DISCUSSION

There are many examples of long- and short-distance dispersal of economic insect
pests and beneficial species from cool-season host reservoirs and/or overwintering
sites. In addition, significant dispersal of these species often occurs during crop and
animal production seasons. The current acceptance of integrated pest management as a
viable concept leading to socially, economically, and technologically acceptable goals
in agricultural production systems means that it is especially important to under-
stand the causes and effects of insect dispersal so it can be manipulated to advantage.
However, pest management focuses on applying control pressure to the entire target
insect population or to a large portion of it, and insects do not recognize country,
state, and county geographical boundaries.

In many cases, knowledge about the dispersal characteristics of important pest and
beneficial species has been instrumental in the development of efficient and effective
control techniques. Such evidence in the past has come from various sources (Williams
1957): (a) direct observation of large numbers of insects flying steadily in a definite
direction, (b) sudden appearance of winged insects in an area where they were not prev-
iously recorded and no local breeding or emergence is known, (c) the presence of insects
at sea or in snow at high altitudes, (d) the presence of insects in an area only at
certain seasons and no stages found at other times of the year, and (e) release and
recapture methodology. In fact, the cited examples of dispersal of several agri-

culturally important pests illustrate this indirect method. The difficulty is that data obtained using these techniques are limited to those that can be obtained at ground level at the point of arrival or departure and so are only a small part of the total. Visual observations of directed flight can be made during the dispersal period, but information is lacking for the airborne phases of insect dispersal. In limited studies conducted as early as 1936 (Glick 1939), airplane sampling techniques employed at levels of 20 to 1500 feet demonstrated that a large number of insect species were present in abundance at high altitudes. Moreover, this finding had economic importance since airborne dispersal relates to the spread of pest infestations. More recently, Callahan *et al.* (1972) demonstrated flights of corn earworm moths above 1000 feet as measured in blacklight traps placed on a television tower.

Thus, airborne movement of many insect species has been demonstrated, but few sampling techniques are available for determining factors affecting migrations or studying the insect during its airborne phase of dispersal. Schaefer (1976) reviewed some of the initial findings obtained using radar techniques to study insect flight and indicated the potential that such methods may have for obtaining this type of information.

The economic importance of arthropods in agricultural production systems and the possibilities of using dispersal behavior to develop and manipulate control appear to justify the development of appropriate remote sensing technology for this purpose.

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DISPERSAL OF FOREST INSECTS

By

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Dispersal is a very important process in the population dynamics of most forest insects. Unfortunately, our knowledge about their dispersal is very limited. I'm sure that at least part of the reason for this lack of information can be attributed to the degree of difficulty and the projected research costs that are anticipated in conducting dispersal studies of forest insects.

Why is dispersal important to forest entomology? Dispersal:

1. Results in expanding the distribution of species.

2. Appears to maintain outbreaks over large geographical areas through continuous mixing of subpopulations.

3. Establishes remote infestations via long-range transport.

4. Negates our ability to predict trends in populations.

Within the major groups of forest insects there are few documented examples of long-distance spread--certainly nothing comparable to the long-range transport of perennial agricultural pests such as aphids, leafhoppers, and grasshoppers. In general, passive dispersal of immature stages is a more important process in the dynamics of forest insects than is the dispersal of adults. Included in this category are the many species that are currently extending their range into new areas such as the red pine scale, Matsucoccus resinosae, beech-scale/Nectria complex, Cryptococcus fagisuda and the gypsy moth, Lymantria dispar. Dispersal is not a major concern in the bark beetles, which is probably one of the most economically important groups of forest insects.

The lepidopterous defoliators are the best examples of forest insect species that exhibit significant dispersal. It's ironic that, in many of these cases, the adult females are wingless or have non-functional wings; this is true of the gypsy moth in the East, Douglas-fir tussock moth in the West, the winter moth in Nova Scotia, and species of cankerworms. These species disperse mainly as newly-hatched larvae that are windblown and are usually attached to silken threads; the silk provides increased buoyancy to the

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larvae by increasing their effective drag. One of the reasons why the spruce budworm, Choristoneura fumiferana, poses such a problem to forest managers is because the insect undergoes three periods of dispersal--newly-hatched larvae in the fall, emerging second instars in the spring, and female moths in mid-summer.

Gypsy Moth

In North America female gypsy moths seldom or never fly--they usually emerge from their pupal cases, mate and deposit their egg mass within a 1-square foot area. The males are known to be strong fliers but there are few references to adult migration in the world literature.

In 1958 nine males of L. dispar were caught in Finland (Mikkola 1967). The insect had never been recorded from that country and the author later detected that the moths belong to a southeast Russian "race." In reconstructing population and weather data, Mikkola concluded that the moths originated from a massive outbreak southeast of Moscow that covered 692,000 A (280,000 ha). Coincidentally, Gornostajev (1962) described a rare mass flight of the gypsy moth near Moscow in that same year. Over a 10-day period, a single mercury-vapor lamp attracted ca. 1,500 moths of which 65% were males, 35% females. This is one of the few references to female moth flight. Mikkola (1971) discovered that there was a period of 62 hours between mass flight near Moscow and the trapping of moths in Finland. By calculating continuous trajectories between the two locations he concluded that the moths covered the 680 mi (1,100 km) by migrating at night along a warm southeastern air current. Low-level jet winds accompanied this trajectory and velocities were recorded up to 52 mph (82 km/h) at the 850 mb level (1300 m).

The gypsy moth has been under study in this country since 1890--however, it's been only within the past 5 years that research has taken an intensive look at male moth dispersal. Yet, knowledge of male moth behavior and dispersal is essential if we are to successfully apply new technology such as pheromones and sterile-male release. Furthermore, detection and monitoring is a critical component of integrated pest management--so it's essential to know what is indicated when a number of male moths are caught in a pheromone trap. Going one step backward, knowledge about dispersal should be applied to design a network of traps.

What is our major concern about male moth dispersal of gypsy moth? For some years now, adult males have been trapped in remote locations such as Virginia and North Carolina that are far-removed from known infestations to the North. Their presence can be explained in one of three ways:

a. Life stages may have been transported that year to an area near the detection trap.

b. There is a spot infestation nearby that resulted from an accidental introduction of life stages in the past.

c. Male moths were transported a considerable distance from an infested area and deposited within range of a trap.

There is still a lot of speculation and disagreement about where the moths are coming from. Since the gypsy moth is a quarantined insect, it's important for planning-regulatory activities that this issue should be resolved.

Spruce Budworm

The spruce budworm is the most destructive defoliator in eastern Canada and Maine. The current infestation covers millions of acres of spruce-fir forest in Maine and New Brunswick alone. Maine claims that moths are blowing across the border from New Brunswick and Quebec. New Brunswick sometimes blames Quebec and Ontario for its influx of female moths.

The behavior of the female moths is such that they fly upwards after dark and accumulate in large numbers below the inversion layer. Under certain conditions, tremendous numbers can accumulate and then be transported for long distances.

According to Greenbank (1957) weather processes give rise to two types of moth dispersal: (1) Convectional transport, in which large numbers of moths are borne aloft and may be carried many miles by the updrafts associated with the passage of cold fronts. Henson (1951) reported on tremendous mass flights of female budworm moths that ultimately deposited moths on Canadian cities; these moths originated from known infestations at least 50 miles (80 km) away. (2) Turbulent wind transport, which is a more local phenomenon important in larval transport. In both cases, the moths are mainly females that contain a portion of their egg complement. Therefore, moth dispersal is an extremely important process in the population dynamics of the species.

Forest Tent Caterpillar

The forest tent caterpillar is a serious defoliator of hardwood trees in parts of Canada and in the North Central United States. Most outbreaks occur sporadically in stands of trembling aspen, _Populus tremuloides_. Brown (1965) reported on the mass transport of forest tent caterpillar adults that were carried by a rapidly moving cold front southward from an outbreak in the forested area of central Alberta for at least 300 miles (480 km) during a 12-hour period. The time of passage of the cold front was synchronized with the maximum flight activity of the moths--late afternoon and throughout the night. The weather in the outbreak area prior to the passage of the front was warm and moist with the maximum temperatures between 85° and 95° F (29° and 35° C). Moth

activity may have been further stimulated by the change in atmospheric pressure associated with the cold front.

Raske (1976) trapped moths of the forest tent caterpillar on the island of Newfoundland in July 1975, that apparently came from an infestation on Nova Scotia, about 150 miles (250 km) away. He noted that a check of several thousand moths that had been transported by air currents in Alberta in 1968 revealed that all were males. Long distance transport of females has not been reported; however, the possibility still exists.

Although I did not attempt to cover the foreign literature on dispersal, I did note one recent reference of interest. Baltensweiler and others (1977) discussed the long-range dispersal of the larch bud moth, Zeiraphera diniana, in Switzerland; this forest defoliator is a serious pest of Larix, Pinus, and Abies.

Conspicuous mass flights have been frequently reported on mountain tops or glaciers, and at the lights of cities. During the last defoliation period in the Alps (1972-1974), three or four exodus flight periods occurred annually and resulted in mass flights that extended over 62 miles (100 km). These flight periods are associated with indifferent barometric pressure over central Europe, light winds, and above-normal temperatures at 6,500 ft (2,000 m).

Summary

Dispersal flights of select species of forest insects are usually associated with periodic outbreaks of pests that occur over large contiguous forested areas. The economic significance of these occurrences is not so important in those species where only the males disperse, with the exception of the gypsy moth. On the other hand, dispersal of females of all spruce budworm species both in Eastern and Western North America is critical to the development and spread of outbreaks.

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Strategic and Tactical Use of Movement Information
in Pest Management

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Good quantitative information on the rate and extent of insect movement is limited for most of our major pest species. Lack of suitable techniques and the high cost involved in determining when and to what extent insects move from place to place are among the reasons for the limited information now available. This is especially true for the species that move long distances.

Yet, we must also acknowledge that research on the movement aspect of insect pest population ecology and behavior has not been given adequate attention because of a lack of appreciation of the importance of information on insect movement in formulating alternative strategies and tactics for pest management.

Entomologists have consistently underestimated the distance that insects fly or drift from one area to another. More disconcerting, they have not adequately considered the dynamics of insect populations and the significance of low level movement in terms of damage the pests can cause at some future time and place. Therefore, we have been slow to formulate concepts of insect control that can nullify or minimize the effects of the movement of damaging pests. Also, I am convinced that the lack of information on the movement of beneficial insects, and recognition of the significance of such information has been one of the major deterrents to the development of the augmentation system of pest control involving programmed releases of parasites and predators.

It is difficult to assess the deterrent effect that inadequate information on insect movement has had on the development and application of more effective and more

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acceptable insect-suppression procedures. When experiments are conducted to determine
the effectiveness of such techniques as the release of sterile insects, use of insect
attractants, release of parasites or predators, planting partially resistant varieties,
and even the use of cultural measures, such tests are generally conducted on a small
scale in non-isolated areas. When results obtained in such experiments are less than
expected the reason is almost invariably attributed to failure of the technique; when
excessive movement of released insects from a small experimental area and/or excessive
infiltration of insects into the experimental area may have been primarily responsible
for inconclusive or poor results. Needless to say improper interpretation of the
results from such experiments can be a deterrent rather than a contribution to the
advancement of pest management strategies.

Insect pest management today for the most part revolves around the use of insec-
ticidal chemicals. Chemicals will continue to be important for insect control for the
future. However, because of such problems as resistance to insecticides, ecological
disruption of beneficial insect complexes due to chemical application and the inherent
limitations of natural controls, especially in our greatly altered agro-environments,
it is vital that scientists continue to support research on more acceptable alternative
methods. However, to make practical use of some of the information already available
on alternative methods and additional information to be expected in the future some
drastic changes must be made in our thinking on feasible and acceptable approaches to
the management of some of our major pests. The rate and extent of movement of the
target pest will be an important consideration in the strategies and tactics to employ.

Most chemical insecticides possess the desirable characteristic of fast-action
in controlling insects. Therefore, it matters relatively little whether a few insects
from some distant area, or even considerable numbers from a nearby area infiltrate
into a farming community. Reliance on routine insecticide applications when control
is necessary will produce immediate control regardless of the source of the pests.
However, most of the alternative methods now under development, including slow-acting
biological agents, release of genetically altered insects, use of insect attractants
and even the planting of partially resistant varieties may have little or no immediate
impact on the insects that move into the area where protection is needed. Therefore,
in order to make optimum use of most alternatives to conventional chemical insecticides
we can not wait until the pest has already reached economic or threatening levels.
The point is that we must seriously consider new concepts and strategies for insect
suppression based on the behavior and economic importance of the pest to be controlled,
and take into account the mechanism of suppression of the various alternative tech-
niques that may be applicable for a given pest.

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Dynamics of Low Level Pest Populations

The importance of insect movement can not be fully appreciated unless there is a reasonably good understanding of the dynamics of the various pests that need to be controlled. The tendency is to regard the movement of a few insects of little or no significance when the population of a pest may have to reach levels of hundreds or thousands per unit area before damage results.

Insects vary in their life cycle and reproductive capacity. Some species have as many as 5 to 10 generations each season. Others require a year or longer to complete one generation. But they all have the capability of a high population growth rate when related to time. If this were not so, they would not become pests.

To emphasize the importance of insect movement I often make use of simple population models (as shown below) that I regard as representative of the average growth rate of many of the major insect pests, starting from a low density level.

Number of insects per unit area starting with a single pair
when the average rate of increase is 5-fold or 10-fold

Generation	5-fold increase	10-fold increase
1	2	2
2	10	20
3	50	200
4	250	2,000
5	1,250	20,000

While the dynamics of most pests is influenced by many variables, and precise information is lacking and may never be obtained for most pests, it is not necessary to have a complex computerized pest model to recognize the practical significance of insect movement. We can use the two growth rates depicted in the simple models and discuss the significance of low level movement of a number of our more important pests. The initial population may begin because of the spread of relatively few individuals from a heavily infested area to a new area, or the movement of a small proportion of a population from an overwintering area to a normally free area during the early part of a new growing season.

The screwworm, a serious pest of livestock is a good example of the significance of long distance movement of a few insects. This pest has been greatly suppressed in the southwestern United States during recent years by the release of sterile flies. Prior to the initiation of this area wide suppression program we had little appreciation of

the full significance of the movement of screwworm flies, even though it was known that this was among the more mobile pests.

The dynamics of a screwworm population starting with a low population is probably well illustrated by the model depicting a 5-fold average rate of increase. The life cycle of the pest is completed in about 3 weeks during the warmer months. Hightower, *et al*. (1965) determined that the insect is capable of flying at least 180 miles, but screwworm infestation rates indicate that some dispersion must occur for even longer distances.

From a practical standpoint if enough mated females emigrated to Texas from Mexico and caused 100 animal infestations during April in the border counties (a highly probable occurrence) and if the number of infestations increases 5-fold each generation (also highly probable), we could anticipate an accumulative total of more than 1 million infested livestock and game animals throughout most of the state before cold weather causes a decline in screwworm activity. Of course the number of susceptible animals eventually governs the rate of increase in the number of infestations that will occur. From the standpoint of fundamental principles of insect pest population suppression, however, it is pointed out here that if the areawide suppression program that has been under way had no greater effect than to reduce the average rate of increase of screwworm cases by one-half each generation, the number of cases originating from 100 early season infestations would be reduced by about 97 percent.

The knowledge and experience gained in the conduct of the areawide screwworm suppression program have relevance to three vitally important aspects of pest management: (1) long range low level movement of a pest; (2) the ability of low populations to increase to highly damaging numbers during a single season; and (3) the importance of applying suppressive measures to the population in a large area in order to nullify or slow down the growth rate.

The pink bollworm in California is another example of the significance of long distant but low level movement of insects. Cotton grown in the Imperial Valley of California is heavily infested with this key pest. The U.S. Dept. of Agriculture and the California Dept. of Food and Agriculture with the strong support of the Cotton Industry instituted a suppression program in 1968 involving the release of sterile moths in efforts to keep the pest from becoming established in the San Joaquin Valley. Highly sensitive sex pheromone traps are employed to monitor pink bollworm conditions in the San Joaquin Valley during the cotton growing season. Every year, native moths are captured in the traps. The numbers captured have ranged from less than 100 to more than 7,000 during a season. Because of the capture of native moths some critics of the program

have concluded that the sterile moth releases are of no value. They believe that the capture of considerable numbers of native moths means that the program is not successful. But, the problem is long distance movement of the pest. The evidence is clear that there is a continuing but variable rate of drift of moths into the San Joaquin Valley, a distance of about 300 miles from heavily infested cotton in the Imperial Valley, and such movement will occur regardless of the suppressive measures used.

Authorities on the pink bollworm would agree that this dynamic pest is likely to increase at the average rate of 10-fold per generation under favorable conditions. There is little question that environmental conditions are highly favorable for pink bollworm development in the irrigated cotton fields during the summer months. Therefore, if a single mated female drifted into a cotton field in June when cotton first starts fruiting, one could expect 2,000 progeny in such field by September and October, which would be about 4 generations later. There is no evidence that such rate of growth of pink bollworm populations has occurred in any localized areas in the San Joaquin Valley during the past 10 years.

This in itself is indirect but sound evidence that the program is achieving its objective. However, in order to make a more critical assessment of the program, I analyzed the native and sterile moth capture data obtained during 1977. By knowing the number of sterile moths released and captured in relation to the number of native moths captured, I calculated by the Lincoln Index Method that during 1977 about 10,000 moths drifted into the San Joaquin Valley from other areas during the period corresponding to the second field generation in the San Joaquin Valley. The rate of infiltration probably tends to be higher as the moth population increases at the source. But a number of unknown factors such as the type of air currents, may be more important than the density at the source in determining the rate of long distance dispersal.

While I am confident that it will be possible to prevent the firm establishment of the pink bollworm in the San Joaquin Valley by maintaining the sterile moth release program, the basic problem is due to pink bollworm migration. The threat to the San Joaquin Valley will continue indefinitely and regardless of the suppression procedures employed, so long as the population is permitted to reach high levels in the Desert Valley areas during the cotton growing season. The only logical solution to the problem in the San Joaquin Valley will be to develop procedures for a rigid, well organized, and fully coordinated pink bollworm population management program in the Imperial Valley and other infested areas within range of direct spread to the Valley.

It should be pointed out that losses directly and indirectly attributable to the pink bollworm in the desert valleys in California and Arizona during 1977 were estimated at $135 million. Moreover, serious ecological disruptions occur in the cotton ecosystem because of the heavy use of broad spectrum insecticides, the principle method of control now employed. Thus, we are concerned with an important economic and environmentally disruptive pest problem that will require a more rational approach to its solution than to rely on the defensive pest management system involving the application of insecticides only where and when populations reach damaging levels.

The significance of insect movement when related to the dynamics of various pests could be discussed at length for dozens of major pests affecting crops, livestock and man. However, I would like to consider another major pest problem. This involves the Heliothis complex. The corn earworm (Heliothis zea) and the tobacco budworm (H. virescens) constitute the nation's most damaging insect species complex. These two related species are widespread and are estimated to be responsible for average annual losses that exceed one billion dollars, (USDA, 1976). The corn earworm attacks many crops and wild host plants. However, it is believed not to overwinter in about the northern third of the country. During the warmer months it spreads northward and causes losses that probably average several hundred million dollars each year in areas where it normally does not overwinter.

The basic population models indicate the significance of such movement. If the migrant population by June averages one pair of moths per acre in the north central region where most of the nation's corn is grown, and if the average rate of increase is 5-fold per generation, the population could grow to an average of 250 moths per acre by late August and early September. This would be enough insects to cause significant damage to field corn and serious damage to more valuable and sensitive crops like sweet corn. Thus, the long range migration problem is probably a more significant factor in the economics of these pests than we realize. This alone would be justification for giving serious consideration to the management of Heliothis on a regional or national scale that will be discussed in the section to follow.

<center>The Total Pest Population Management Concept and
Strategies and Tactics That Might Be Used in the Future</center>

Recognizing the important role that insect movement plays in the dynamics and economic significance of most of the major pests, I have strongly encouraged research on suppression methods that might be technically and economically feasible, and which would also be ecologically acceptable when applied on an area wide basis. The purpose

of such method would be to prevent the development of economic populations throughout a pest ecosystem. For some pests like the _Heliothis_ species this would necessitate regional programs involving many states.

I agree that the most logical way to cope with many of the hundreds of relatively minor pests that appear sporadically in localized areas will be to apply appropriate suppressive measures only where and when the pests become damaging. This will also be necessary for annually recurring major pests until we can develop and put into practical use more effective and acceptable methods. However, for the more damaging pests, many of which cause losses exceeding $100 million each year, I have urged that scientists in pest management give serious consideration to the suppression and management of the populations in an organized and fully coordinated way so as to prevent the development of economic populations in areas where they are of critical importance. The option we have for controlling pests after they reach damaging numbers during a growing season is now largely limited to the application of insecticides. We may be forced to rely on fast acting chemical or fast acting biological insecticides to cope with virtually all of our insect problems so long as we advocate chief reliance on natural controls until pests reach economic threshold populations. The importance of natural control agents as aids to the regulation of insect pest problems must be fully recognized. But we must also recognize the limitations of natural controls. The defensive farm-to-farm pest management strategy has been relied upon for up to a half century for the boll weevil, pink bollworm, codling moth, _Heliothis_ and virtually all other major pests. The result is that populations of most of our major pests are as high or higher today than they were 10, 20 or 30 years ago and losses continue largely undiminished and in some cases are steadily increasing. I might say that _Heliothis_ _zea_ is used as a model insect problem by some of the strongest advocates of the integrated pest management concept that relies on natural controls until pests reach levels that justify the cost of control. However, I urge that members of the entomology profession, top level program administrators in all agencies concerned with the formulation of public policies and financial support for pest management programs, and those who are concerned with the environmental impact of pest control strategies and tactics, take a critical look at the degree of success of this approach to _Heliothis_ management, and what it holds for the future. Should we continue to rely on the defensive strategy as the best solution to these and many other major pests for the indefinite future? I have already cited the 1.2 billion dollar loss, nationwide, attributed to the two _Heliothis_ pests. But we may also consider the _Heliothis_ situation in California where every effort is made by entomologists to encourage primary reliance on natural controls for these pests. I agree that we should take maximum advantage of the many natural biological control agents for these pests. This is why the development and use of

target pest specific control measures would be so desirable. But in my opinion self-perpetuating biological control agents alone cannot maintain populations low enough under modern agricultural practices to keep losses on all crops attacked at acceptable levels.

Each year the California Department of Food and Agriculture (1976) issues estimates of damage and crop losses caused by insects and mite pests. The estimated assessable yield loss for Heliothis zea during 1976 was $55,411,000. In addition, however, the cost of control (largely insecticides) was estimated to be $29,365,000. In my view the total loss of $84,776,000 makes it self-evident that a completely different approach is needed in order to achieve a more effective and a more acceptable solution to this pest problem. I would like to add that the related tobacco budworm, which was of no importance in California until the past few years, has now become a major pest. This relatively new problem accounted for many millions of dollars in losses during 1977 and required heavy use of ecologically disruptive insecticides in southern California.

I am confident that there can be a better way of coping with the Heliothis problem if we will give more consideration to the total population management concept, utilizing basic techniques that we now have or could develop. When we look at a relief map of California it is apparent that this important agricultural area is largely an ecologically isolated agro-ecosystem. Despite the long range movement of pests like H. zea and H. virescens, effective population management should be possible at a cost that would be only a fraction of current costs of chemical control.

Let us consider another major pest, the boll weevil, where insect movement is a critical factor in its proper management. I regard this insect the most obnoxious pest in the United States. It has been responsible for billions of dollars in losses and has required extensive and intensive use of ecologically disruptive insecticides. About 20 years ago, I calculated that if a starting overwintered boll weevil population averaged 200 per acre in a cotton growing community, and if 90 percent of the growers apply control measures diligently but 10 percent fail to apply control measures or do a haphazard job, enough boll weevils will be present by the F3 generation (when extensive local movement of the insects generally occurs) to cause 100 percent square or boll infestations on all of the cotton in the community. This could be expected even if the growers who were diligent in applying control measures had killed 100 percent of the boll weevils up to that time on their own farm. Such incomplete and unorganized system of boll weevil management also virtually assures a threatening overwintered population every year. I also calculated that if the population was suppressed by

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no more than 80 to 90 percent each generation on all of the farms, the total population should be held to a level of little significance.

The calculations, which should be recognized as a fundamental principle of insect population suppression, convinced me that there is only one rational way to deal with this dynamic pest, and that will be to adequately manage the total population in every community where the pest is of major importance or attempt to eliminate the pest completely. My views on this matter have not changed. I have the same conviction for a number of other major pests.

Entomologists are making slow but steady progress on ecologically acceptable techniques of suppression that might make the total pest population suppression concept feasible and practical for a wide range of pest problems. There are three methods of suppression that are virtually pest specific; and therefore would be entirely acceptable from an ecological standpoint. These are: (1) programming the release of large numbers of highly pest specific parasites or predators throughout a pest ecosystem; (2) the release of sterile or genetically altered insects; and (3) the use of insect attractants, such as sex pheromones. These techniques possess what I call mobile suppressive action. They are capable of reducing reproduction of insects in every part of a pest ecosystem, which would mean that reasonably uniform suppressive pressure would be applied against the total population. The efficiency of certain techniques of insect control vary with the density of the pest populations. The autocidal technique and insect sex attractants are most efficient when the target pest population is low. Therefore, prior suppression of a population with chemical and/or cultural measures may be necessary to reduce populations to effective manageable levels by these techniques. The parasite augmentation technique, however, should have maximum efficiency when the target pest population is high and because of their unique host finding mechanisms released parasites and their progeny can be expected to apply suppressive action where and when host densities are highest and where suppression is most urgently needed. Therefore, for some pests we may be able to employ two techniques concurrently or sequentially that would be highly complementary in suppressive action without the necessity of prior reduction by methods that could cause serious ecological disruptions. A fourth and highly desirable method of control is to develop resistant plant varieties for some of the plant pests. This is a proven method of plant pest control, but here again, united action may be necessary if the available varieties are only partially resistant. Unfortunately, however, this method is not applicable for many of the nation's most costly pests. Also some species attack a number of crops and resistant varieties for all crops affected are not likely to be developed.

In approaching insect pest problems from the total population suppression concept, it is of course necessary to consider the life history, behavior and dynamics of each species. The time, rate and distance of movement will be one of the most important behavioral characteristics to take into account. Such information will be needed to determine when and where to apply suppressive measures, the degree of suppression neces-sary, and the size of the area that will have to be included in a fully organized and coordinated suppression program.

Effective management of pests like the corn earworm and tobacco budworm may necessitate programs on a regional or national scale involving millions of acres of host plants and many thousands of square miles of farming areas. The degree of suppression required may not have to be too high, however, to be adequate. Referring again to the basic population model, if the average rate of growth of a pest population is reduced by one half each generation the number of insects present after 3 generations would be reduced by 87.5 percent.

Area wide suppression programs will require critical monitoring of the pest condi-tions. They will challenge the imagination and ingenuity of our research and pest management authorities. However, this should not deter our thinking on the most practical long range solution to major pest problems. The potential costs and benefits, both economically and environmentally, of this strategy as compared with current practices should be critically analyzed. Based on theoretical calculations, I think the prospects are excellent for eventually managing the corn earworm and the tobacco budworm populations by the mass production and release of billions of parasites and/or billions of genetically altered moths with limited use of supplemental suppressive measures in critical situations. In view of the progress already made on the mass production of insects and the prospects for even greater advances in the future on this vitally impor-tant aspect of entomology, the costs for rearing the number of insects required for effective area wide management may be less than the annual expenditure involved in the use of ecologically disruptive chemical insecticides. I have estimated that certain larval parasites of Heliothis may eventually be mass produced at a cost of $3.00 per 1,000 (Knipling, 1977). If this is an attainable goal, 5 billion parasites could be mass produced for half the estimated 29 million dollars spent on chemical control in California in 1976. This would permit the release of 500 parasites per acre each generation on 10 million accumulative acres of susceptible crops during the season. Theoretical calcu-lations indicate that this should provide effective control (Knipling, 1977). Therefore, if such strategy would accomplish adequate control, the cost would be less than present chemical control costs and the annual loss of $55 million might largely be eliminated.

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A number of important insect pests may be amenable to area wide management of similar procedures applied to pests at a strategic time. Several important species including the fall armyworm, the cabbage looper and velvet bean caterpillar are among the major pests known to have greatly restricted overwintering areas. Each summer season they spread for hundreds of miles and attack a number of important crops in areas that may exceed the size of the overwintering area by 10-fold, and after the pest populations have increased by 100 fold or more.

I would like in particular to discuss the fall armyworm. In my opinion, this species is an excellent example of a major pest that might be dealt with in a highly effective manner by attacking the total population at "a strategic time and place." The objective would be to reduce the population to such a low level that it would not reach highly damaging levels by the time cold weather again causes a natural decline in the population. I do not know how the name "fall armyworm" originated. But knowing of its restricted overwintering area, this in itself suggests that it is generally late in the growing season before the pest has become widespread and has had time to increase to population levels that cause major damage to crops.

The distribution of the fall armyworm in the United States during the winter and the rest of the season is shown in figure 1. This distribution map is based on data compiled by Snow and Copeland (1969). The map indicates that the fall armyworm population normally overwinters in the southern half of Florida and in south Texas. From this greatly restricted area it spreads throughout much of the United States by late fall. No doubt the population that overwinters in Texas and along the Gulf Coast during mild winters and the Florida population overlap in the summer and fall. However, it is probable that the Florida population is responsible for most of the losses in the southeastern states.

It does not require a great deal of rationalization to conclude that a logical solution to the fall armyworm problem in the southeast would be to attack the population in Florida during the winter, if appropriate suppressive techniques could be developed. In my view a great deal of progress has already been made on the basic technology needed to accomplish effective suppression of the overwintering population. I do not wish, however, to underestimate the magnitude of the research and development effort that would be required to perfect the technology needed to manage effectively the fall armyworm population in Florida during the winter and the amount of ecological information about the pest that needs to be obtained in the overwintering area before an effective program could be planned. At the same time I have full confidence in the ability of our scientists to develop the information and the technology required for an effective suppression

program. I believe this could be accomplished at a cost that would.not exceed one tenth the average losses caused by the population that spreads through the eastern portion of the United States.

The greatest hurdle is likely to be acceptance of the concept by the entomological community and then gaining the support of the agriculture industry for financing the total population management approach for the solution of this major pest problem. But I wish to raise this question: What are the prospects for developing effective and acceptable alternative procedures? Shall we continue to take the defensive posture and attempt to control the pest on a farm-to-farm basis after it has spread and increased to high populations in a dozen states?

In my opinion, we have two techniques of suppression that could be developed and utilized as the principle means of suppression. These are the programmed release of appropriate biological agents on a large scale and the concurrent release of sterile or genetically altered insects. In addition, strategic use may have to be made of supplementary suppressive measures in localized areas including chemical or preferably biological insecticides. The use of the fall armyworm sex pheromone would be a vital tool for surveys and population assessments. It is also possible that the pheromone and so called mating inhibitors could play an important role in suppression.

The magnitude of the costs and benefits is, of course, the governing element in planning the strategies and tactics that might solve a pest problem. The fall armyworm, however, is among our most costly pests. Insecticides are now required for its control. Not only is this a costly control method but their use results in residues on forage and food crops and they cause the usual ecological disruption. The amount of damage caused by the pest varies greatly from year to year, but probably averages in excess of $100 million per year in the southeast.

In order to illustrate what might be expected from a fall armyworm suppression program in Florida, I will again rely on hypothetical population models. The models for an uncontrolled population and for a population suppressed by 95 percent during the winter months in Florida are shown in Table 1.

Admittedly, the size of the original migrant populations, and the 10-fold rate of increase assumed may not be very accurate. However, I believe that the assigned values are sufficiently realistic to illustrate the nature of the fall armyworm problem and the results and benefits that might be expected from a rigid population suppression program. Whether the initial migrating population consists of 1 million, 5 million, or 25

million, or whether the rate of increase per generation averages 5, 10, or 15-fold, are not necessarily critical parameters at this stage in our thinking on the general strategy that might be used to manage this major pest. I do believe, however, that if the normal overwintered population could be suppressed by 95 percent, this would be reflected by a similar magnitude of reduction in the amount of damage the pest would cause in its normal area of spread. One word of caution - we should not overlook the possibility that Cuba and other islands in the Caribbean area could be the source of significant numbers of fall armyworms in Florida and other Atlantic and Gulf Coast states.

The reduction of an overwintered population by as much as 95 percent may not be a difficult or costly problem. If two generations of the pest normally occur during the winter before there is significant long range dispersal, suppressive measures that would reduce the normal reproductive rate by 80 percent each generation should reduce the population by 96 percent by the time northward migration begins.

The assignment of the same rate of increase for a normal uncontrolled population and a greatly suppressed population may be subject to question. This ignores the possibility that there will be less action by density dependent suppression forces against the greatly reduced population. However, it is my opinion that an insect that spreads rapidly and for long distances will not be subjected to strong action by density dependent biological agents until the populations reach or approach the economic density level.

It should be noted that the system of reducing a pest population during the winter when it exists in a greatly restricted area, in order to reduce the number that can move into other and larger acreages of crops later in the year, is not a new concept. The feasibility and effectiveness of this approach has already been demonstrated in Idaho for the beet leaf hopper, a long distance migrant (Douglass and Cook, 1952). By re-seeding range areas with grasses to replace natural wild host plants, beet leaf hoppers were reduced to levels that were of little importance in cultivated areas up to 100 miles distant. Green peach aphid populations in the state of Washington have also been reduced to levels of little economic importance by burning weed hosts in overwintering places so as to protect sugar beets (Wallis and Turner, 1969) and on peach tree hosts to protect potatoes from diseases transmitted by this important vector of a number of plant diseases (Powell, 1967).

General Comments and Conclusions

Several insect problems have been discussed in a general way in which the movement of
the insects is unquestionably a major factor influencing the economic importance of the
pests and has limited the success of the suppressive measures now employed. Much more
information than is now available on many insects is needed to make a better appraisal of
the practical significance of the insect dispersal problem. There is little doubt,
however, that this is a problem of major importance for a majority of the nation's more
important insect pests. Perhaps more definitive data on the time, rate, and extent of
movement of a number of major pest species will yield the type of information needed to
crystalize our thinking on the best strategies and tactics to strive for in the long
range goals of achieving more effective and more acceptable solutions to some of the
nation's key insect pest problems. Hopefully, this workshop will contribute to the
development of better techniques for measuring insect movement. This in turn should
lead to a better understanding of the importance of insect movement in the development
and implementation of more effective and ecologically acceptable pest management
strategies and tactics.

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Table 1. Hypothetical population models projecting the dynamics and economic losses due to an uncontrolled migrant fall armyworm population originating in Florida, compared with the dynamics and economic losses due to a migrant population suppressed by 95% during the overwintering period in Florida

Generation & Time Period	Unsuppressed Population		Winter Population Suppressed by 95% in Florida	
	Total Moth Population [1]	Acreage of Crops Damaged[3]	Total Moth Population [1]	Acreage of Crops Damaged[3]
1 April–May	5,000,000[2]	—	250,000[2]	—
2 June	50,000,000	—	2,500,000	—
3 July	500,000,000	500,000	25,000,000	—
4 August	5,000,000,000	5,000,000	250,000,000	250,000
	5,500,000 acres X $20 avg loss/a = $110 million		250,000 acres X $20 avg loss/a = $5.0 million	

[1]The model assumes an average increase rate of 10 fold per generation.

[2]Assumed starting migrant population.

[3]Based on the estimate that as few as 500 females per acre will cause significant damage to susceptible crops.
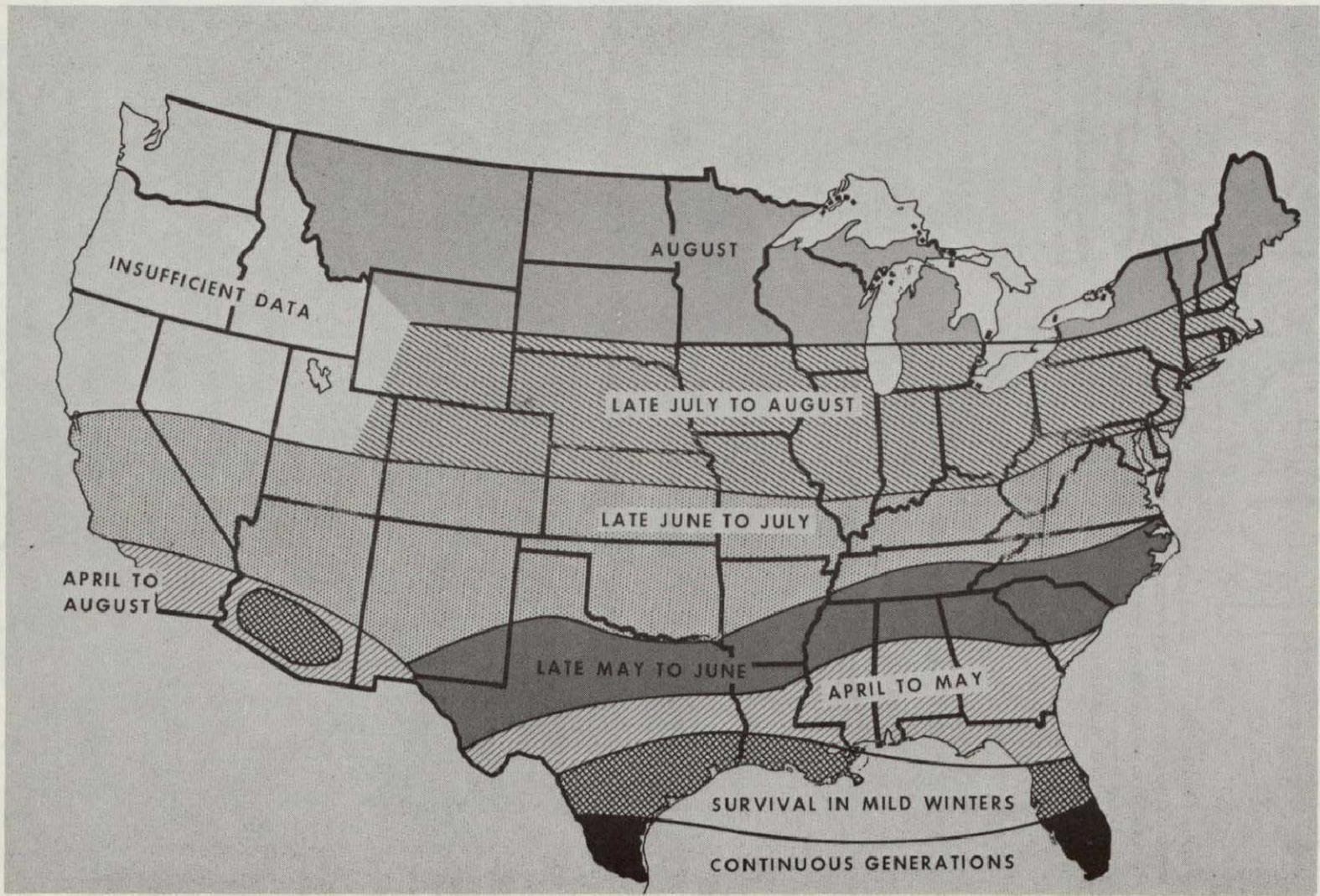
Figure 1. Annual northward progress of fall armyworm and areas of continuous generations and of survival in mild winters in United States. [Data compiled by Snow and Copeland (1969), from Cooperative Insect Survey Report].

THE POSSIBLE ROLE OF ATMOSPHERIC PROCESSES IN INSECT MOVEMENTS

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(Paper Not Submitted For Publication)

CAPABILITIES OF RADAR AS THEY MIGHT RELATE TO ENTOMOLOGICAL STUDIES

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INTRODUCTION

An individual insect may be a small target for detection by a conventional radar, but radar has been able to detect and track individual insects as well as swarms. Insects have proven to be a strong source of clutter on some high-power aircraft-surveillance radars, so much so that they can limit the ability of the radar to see the desired targets especially at short ranges. Generally, the deleterious echoes from insects can be removed by use of a time-varying gain (STC, or Sensitivity Time Control), as well as by the proper design of MTI (Moving Target Indication). Radars have also been used to good effect in studying the behavior of insects, including flight characteristics and the tracking of individual insects or swarms. The backscatter characteristics of many insects have been measured, as have the characteristic amplitude modulations of their echoes.

The purpose of this paper is to provide a tutorial background on radar capabilities and its potential for insect research. It is one of the papers prepared for the Workshop on "Radar, Insect Population Ecology, and Pest Management," sponsored by NASA and the U.S. Department of Agriculture held at Wallops Island, Virginia, on May 2-5, 1978. This paper is intended for those entomologists and pest-management scientists with little or no knowledge of radar.

The basic principles and concepts of radar will be reviewed along with a description of the type of information that can be provided by a radar. Particular issues relating to the use of radar for insect research will be addressed and examples of current radar equipments that might find application for insect research will be mentioned. Because of the limits of time at the Workshop, the treatment of these topics will not be in depth, but will be primarily a review highlighting the important aspects.

- BASIC CONCEPT OF RADAR

A radar detects the presence of a target and determines its location and other information by radiating an electromagnetic signal, detecting its echo from reflecting targets, and comparing any changes in echo signal relative to that which was transmitted. A "typical" radar (if there is such a thing as "typical") might transmit a train of pulses, each perhaps one microsecond (10^{-6}s) in width, at a repetition rate of the order of 100 Hz (cycles per second), with a peak power of 1 Mw (10^6 watts) and an average power of 1 kw (10^3 watts). The antenna beamwidth might be of the order of one degree and the wavelength might be about 10 cm. (There are, of course, a wide range of variations to these characteristics. This is but one particular set. Insect research radars, for example, generally would operate with shorter wavelengths.)

The typical radar measures the distance (or range) to the target and its location. The width of the pulse determines the accuracy of the range measurement and the ability to resolve nearby targets. A 1 µs pulse width corresponds to 150 m of spatial extent. A 1 ns pulse width (10^{-9}s), which is within the capability of modern radar technology can provide a resolution of 0.15 m (about one-half foot). The pulse repetition frequency is chosen high enough to obtain a large number of echoes as the radar scans by the target; but low enough to avoid ambiguities, or second-time-around echoes, from larger targets at long range. (A 1000 Hz pulse repetition rate corresponds to an unambiguous range interval of 150 km, or 81 nautical miles.) A beamwidth of one degree requires an antenna aperture of about 60 wavelengths. At a 10 cm wavelength (S-band) the antenna dimension would be 6 m, and at 3 cm wavelength (X-band) it would be 1.8 m. Appendix I provides some of the equations useful for radar analysis, including those from which the above numbers are derived.

A moving target produces a <u>Doppler frequency shift</u> that is detectable by radar. It is expressed by

$$f_d = \frac{2v}{\lambda} \cos \theta \tag{1}$$

where v = target velocity, λ = wavelength, and θ = angle between target's vector velocity and the direction from target to radar. The doppler frequency shift is employed in radar to separate moving targets from the fixed clutter background. It is also possible to measure relative velocity by this means, except that in practice the measurement often contains unavoidable ambiguities.

Much can be learned about a radar by an examination of the <u>radar range equation.</u> One form is

$$R^4 = \frac{P_t G^2 \lambda^2 \sigma \, nE_i(n)}{(4\pi)^3 kT_0 BF_n(S/N)L_s} \tag{2}$$

where P_t = peak power, watts

G = antenna gain, relative to isotropic

λ = wavelength, meters

σ = effective radar cross-section of the target, sq. meters

n = number of pulses returned from target (hits per scan)

$E_i(n)$ = the efficiency with which these n pulses are added, or integrated

kT_o = the Boltzmann's constant times the absolute temperature = 4×10^{-21} watts/Hz

B = receiver bandwidth, Hz

F_n = receiver noise figure

(S/N) = the signal-to-noise ratio (on a single pulse basis) required for reliable detection (a number ranging from 20 to 100, or 13 to 20 decibels)

L_s = system losses, can range from a factor of from 4 to 50.

By substituting $P_t = P_{av}/\tau f_p$, where P_{av} = average power, τ = pulse width, and f_p = pulse repetition frequency into Equation (2), we get

$$R^4 = \frac{P_{av}G^2\lambda^2\sigma E_i(n)\ t_o}{(4\pi)^3 kT_o G_n (S/N)} \tag{3}$$

where the usual relation $B\tau = 1$ has been used and $n/f_p = t_o$ = time duration of observation of the target. To achieve a long range requires:

(1) large average power

(2) high antenna gain (large aperture and narrow beamwidth)

(3) long time of observation

(4) sensitive receiver

In addition to attaining the necessary range as determined by the radar range equation, there are several other factors that will restrict the range. One such factor is the distance to the line of sight, which is determined by the curvature of the earth and the heights of the antenna and target. For a radar at height h_a and a target at height h_t the distance to the line of sight is

$$d = 1.23 \left(\sqrt{h_a} + \sqrt{h_t}\right) \tag{4}$$

where h_a, h_t are in feet and d is in nautical miles. For the type of targets of interest to entomologists, the range will be determined to large extent by the masking of terrain features and by unwanted echoes from terrain and other natural objectives (clutter).

In addition to the simple pulse radar mentioned above, other waveforms may be utilized. Some of the common types of radar waveforms are briefly:

Simple Pulse - This is the common type of radar waveform.

High-Range Resolution - Resolution from a few centimeters to several meters, useful for seeing desired targets in clutter. High resolution is often accomplished with pulse compression, a technique for achieving the energy of a long pulse but the

resolution of a short pulse by frequency or phase modulating a long pulse.

CW (Continuous Wave) - A continuous-wave transmission has some advantages for extracting the Doppler shift, but does not provide a range measurement. Usually separate transmitting and receiving antennas are required.

FM-CW - By adding a wideband modulation to the CW carrier, range can be determined. Doppler shift can also be obtained.

MTI (Moving Target Indication) - A pulse radar that detects the Doppler frequency shift for the separation of moving from fixed targets. Usually the Doppler shift measurement is ambiguous.

Pulse Doppler - Similar to MTI except that Doppler measurement is usually unambiguous, but range measurement is ambiguous.

Synthetic Aperture (SAR) - An airborne imaging radar capable of high resolution in both range and angle; can be 3 m resolution. (The utility for insect research is probably marginal, except when large, dense clouds of insects are to be observed.)

The major subsystems of a radar are (1) antenna, (2) transmitter, (3) receiver, (4) signal processor, (5) data processor, and (6) display. There are many possible variations to each of these. The display is what the user interacts with most. The various displays commonly used in radar are:

PPI (Plan Position Indicator) - A circular coordinate system plotting range and azimuth angle. An intensity modulated display in which presence of targets is indicated by a blip of intensity. Advantage is a map-like presentation. Disadvantage is the limited dynamic range and the absence of amplitude information.

A-Scope - A plot of amplitude vs time (range). Its advantage is that it provides a larger dynamic range than the PPI, and the amplitude information can be extracted from the display. Its advantage is that it cannot be used with a scanning antenna because the information displayed changes too rapidly.

RHI (Range-Height Indicator) - An intensity modulated display of a cut in the vertical plane (range and elevation angle) at a fixed azimuth. Useful for determining target height and orientation in the vertical.

B-Scope - Similar to the PPI but with a rectangular display (range and azimuth angle). Its advantage for insect research is that it can display close-in targets without the crowding normal with a PPI.

It should also be mentioned that radars can be provided with automatic detection and tracking (ADT) which displays established and processed target tracks rather than raw video. This is sometimes called synthetic video. Such equipments are rapidly becoming readily available. ADT can provide tracks of several hundreds of individual targets, but would probably not do well in tracking swarms of insects. An operator with a grease pencil might do better.

INFORMATION EXTRACTED BY RADAR

A radar extracts information about a target by comparing the nature of the received signals with the signal that was transmitted. Table I lists in summary form the basic measurement capabilities of radar. To extract information the radar utilizes the following measurements:

> time delay (range)
> angle of arrival
> Doppler frequency shift
> echo amplitude fluctuations
> absolute magnitude of echo
> polarization response
> track history.

With respect to insect research a radar might provide the following about a single insect:

> approximate size
> track (in range, azimuth and elevation)
> aspect ratio
> wingbeat frequency
> relative velocity.

For a swarm of insects, the following might be possible:

> size of swarm
> direction and speed of travel
> number of density.

The ability of a radar to extract information will be limited by echoes from undesired objects in the vicinity of the insects such as the ground, vegetation, trees, and man-made objects. Observations in rain will also be difficult.

SPECIFIC ISSUES RELATING TO INSECT-RESEARCH RADAR

Target Cross-Section

The radar cross-section of insects is quite small, being in the range of from 10^{-3} to 10^{-5} sq m at the higher microwave frequencies. (Note that the radar cross-section is not related in a simple manner to the physical area of the target, in most cases.) The detection of individual insects will require high-power radar and short-range, or both. Since

the backscattered energy varies as R^{-4}, there is considerable benefit in limiting observations to short range. For example, a radar capable of detecting a 1 sq m target at a range of 200 nmi (not unusual for high-power aircraft-detection radar) will see a 10^{-4} sq m target at a range of 20 nmi. If the radar is observing n insects within its resolution cell, the effective cross-section is n times that of an individual insect. Thus swarms of insects can be seen at larger range. For example, a one degree pencil beam radar with a 1 μs pulse sees at a range of 20 km a volume of almost 2×10^{7} cubic meters. One insect per 1000 cu m, each with a 10^{-4} m^2 cross-section, results in a total cross-section of 2 sq m.

Radar Frequency

The target cross-section, and therefore, the capability of the radar is a function of the frequency. The maximum cross-section for an insect should occur when the radar wavelength is comparable to the circumference of the insect (this is the so-called resonance region). Thus the radar should operate somewhere in the range from 3 cm to perhaps one mm wavelength. (The actual wavelength will depend on the shape of the insect and its dielectric properties.) The resonance region is usually quite broad so that a wide range of frequencies are probably available from which to choose. One rule of thumb mentioned in the literature on insect research is that the radar wavelength should be no more than three times the dimension of the insect. This is not a fundamental restriction. It can be violated if the radar is powerful enough. When the wavelength is large compared to the target dimensions, the cross-section varies as λ^{-4} (the so-called Rayleigh region). A high penalty is had by operating at the longer wavelengths, or lower frequencies. However, it is easier to obtain high transmitter power, large antennas, and sensitive receivers at the longer wavelengths. Thus if lower frequencies are desired, they should not be dismissed without detailed examination. The usual bands that might prove of interest are at wavelengths of 5 cm (6 GHz), 3 cm (10 GHz), 2 cm (15 GHz), 8.6 mm (35 GHz), and 3.2 mm (94 GHz). At wavelengths shorter than 3 cm the atmospheric losses increase rapidly. This is one of the major limitations in the use of millimeter wave region. Radars at millimeter wavelengths are practical only for short range or at high elevation angles where the atmospheric losses are less than at zero degrees elevation angle.

Tracking

There are at least three different methods that can be used for the tracking of targets with radar. One is with a conventional pencil-beam tracking radar (using conical scan or monopulse angle-error sensing) which locks on and tracks a single target or a

collection of targets of small physical extent. The second is the use of a rotating fan-beam antenna, as in a conventional surveillance radar, that allows many targets to be tracked simultaneously. Tracking may be by any operator marking target positions from scan to scan with a grease pencil on the face of a cathode-ray-tube (CRT) display. This allows the tracking of single targets or even a swarm (cloud) of targets. Single-target tracking may also be accomplished automatically (ADT). Several hundreds of target tracks may be handled with aid of a minicomputer. Data rates of from 4 to 12 seconds are typical for such radars. A surveillance radar used in this manner for the tracking. of targets is called track while scan (TWS). The third method is also called track while scan, or sometimes scan track. It is usually accomplished at a higher data rate (0.1s) and over a limited sector (perhaps 30°) with a radar specifically designed for this purpose. A cloud-like target is probably best tracked manually with a track-while-scan or a scan-track radar since dedicated monopulse or conical scan trackers have difficulty maintaining lock on a distributed, fluctuating target. A dedicated tracker or a single pencil-beam radar, however, can be manually controlled by an operator to sector scan the region of interest, similar to the scan-track but at a lower data rate. This has proven to be an acceptable procedure for research radars.

Target Recognition and False Alarms

It should be possible for a radar to recognize a single insect by its characteristic small cross-section and/or its characteristic track history and to distinguish it from other targets. Swarms of insects, however, might be more difficult to distinguish from birds or meteorological effects. At present there does not seem to exist a reliable criterion for distinguishing insects from these other targets, which can be classed as false alarms, but there do exist some possibilities that might prove of some help. The characteristic insect wingbeat frequency observed in radar echoes can possibly be used to separate them from some meteorological echoes. Birds also produce a characteristic wing-beat that might be difficult to separate from that of insects. However, distributed targets also produce an amplitude fluctuation of the echo signal that can fall within the frequency ranges reported for insect wingbeats. (The amplitude fluctuation expected from a distributed moving target is discussed in Appendix II.) It is possible that the amplitude fluctuations from a distributed moving target might mask any modulation of the echo due to the insect wingbeats. The wingbeat frequency or the echo amplitude modulations of a distributed cloud of insects might prove useful for separating these echo signals from the unwanted echoes caused by stationary ground clutter such as vegetation, trees, and rocks. Another technique that might provide some utility for recognizing insects is to examine the differences in their echoes when orthogonal polarizations. are transmitted.

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Also, the dielectric properties of insects are different from those of birds and weather, and might result in scattering characteristics that provide a means of recognition. The frequency dependence of the scattering from meteorological effects is different from that of insects (cross-section of clear-air turbulence varies as $f^{1/3}$, but varies as f^4 for insects, where f = frequency). However, the frequency variation of birds is similar to that of insects.

Clutter, or Unwanted Target, Reduction

It is quite likely that radar will be required to observe insects in the vicinity of the ground, nearby trees, or vegetation. Unwanted reflections can occur from such objects which can clutter the display and make difficult or impossible the detection of desired targets. One method of reducing the effects of clutter is to use radars with narrow beamwidths and short pulsewidths that can resolve the insects from the background clutter. Short pulsewidths, however, generally mean reduced sensitivity, especially for a distributed target like a swarm of insects. Pulse compression can be used if sensitivity is important. The Doppler frequency shift from moving targets can also be used to reduce the effects of stationary clutter. However, most of the current radars that employ processing are optimized for the detection of moving aircraft and would probably not perform well with insects. A special radar design is probably necessary if insects are to be discriminated from clutter on the basis of the Doppler frequency shift.

Another problem is the so-called second-time-around echoes that can occur from distant clutter and other targets when the pulse repetition frequency is so high that range ambiguities result. That is, the echoes from previous pulses are received during the anticipated reception period of the last pulse transmitted, and therefore produce ambiguous range measurement and result in distant clutter appearing simultaneously with near-in targets. Proper radar design and siting can avoid this problem to large extent.

A low-sited radar looking up at insect targets will not be bothered with clutter echoes as will a high-sited radar looking down on the targets. This makes the airborne observation of insects difficult, if not impossible, in many situations. If airborne radar is to be used, the insects must be at a sufficiently high altitude and the aircraft or helicopter must be at a sufficiently low altitude to avoid backscatter from clutter that can mask the targets of interest. Alternatively, a radar in a (relatively) high-altitude aircraft can be designed to detect insects by looking down at lower altitude and range gating (switching out) the ground clutter. This assumes the radar has a sufficiently short pulsewidth to eliminate the background clutter and still detect the insects that fly above the clutter. It also assumes the insects are sufficiently separated in altitude from the underlying clutter.

The type of radars to be used for insect research will likely have no capability for observing insects in the rain.

Radar Transmitter Power

Radars can radiate large power, although most of the radars used thus far for insect research have had but modest power. It has been mentioned that birds being tracked by high-power radar can sense the radar radiations and sometimes act as if they are trying to escape from the radar beam. Flocks of birds have also been reported to scatter when being illuminated by the radar beam. On the other hand, other experiments fail to detect any effect of the radar on birds. The biological effects of electromagnetic radiation on humans are well known. In insect research with radar, the possibility should be tested that the insect and its behavior might be affected by the presence of radar radiation. It is something that should be kept in mind.

Capability of a Radar to Ascertain Atmospheric Processes

There have been many reports in the radar-meteorology literature of the use of radars to observe atmospheric processes. Examples include the observation of convective cells (thermals), Bernard cells, turbulent layers, internal waves, Kelvin-Helmholtz instabilities, tornadic vortex signatures, internal flow fields of severe storms, and wind flow in the normal atmosphere by means of chaff particles (aluminum foil strips) tracked by multiple Doppler radars. Reflections from clear-air turbulence are quite weak, and can have cross-sections comparable to that of individual insects. The radars used for atmospheric observations are not simple, and a radar designed for insect research might have only limited capability for the observation of atmospheric effects. One of the problems of insect research will be the separation of insects' own motions and travel from that of the meteorological effects that might be driving them.

EXAMPLES OF RADAR EQUIPMENTS

In this section some examples will be given of existing radars that might be used for insect research. The first two mentioned below represent the smallest (and cheapest) that might be used and the largest that might be used.

Commercial Marine Radar

These are inexpensive X-band (3 cm wavelength) radars of low power. (The highest average power being 20 w.) Such radars have already been reported as being used for insect research, with the shipboard fanbeam antennas being replaced by a parabolic reflector producing a pencil beam.

AN/FPQ-6

This is a long-range instrumentation radar widely used by NASA for the tracking of spacecraft. It has been employed in the past to study birds and can be used for insect research. There are a number of these radars located throughout the world, and they might be used for insect research on a not-to-interfere basis with their other functions. It is a powerful radar operating at C-band (5 cm) with a 20 ft diameter monopulse-tracking antenna, 2.8 Mw peak power, 5 kw average power, pulse widths from 0.5 to 5 µs, and a beamwidth of 0.5°. It can track a 1 sq m target at 600 nmi, or a 10^{-4} sq m target at 60 nmi.

AN/MPS-36

This is a mobile instrumentation radar, also operating at C band. It has a 12 ft antenna (with a 1.2° beamwidth), 1 Mw peak power, and 1 kw average power. It has far less capability than the AN/FPQ-6; but, it can be moved and emplaced on a prepared site, and it can provide tracking capability within eight hours using a four-man crew.

AN/APS-116

This is an airborne radar, but it has been used in a van for ground-based application. The chief interest in this radar is its unique capability to obtain by the use of pulse compression a range resolution of about 0.5 m. It is an X-band (3 cm) radar with 500 kw peak power. It has a detection capability of about 15 nmi against a one sq m target. With land-based operation, greater performance can be obtained by replacing its dB gain antenna with a 40 or 44 dB gain (7 or 9 ft diameter) reflector.

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NRL Combination K_a and X-band Radar

An experimental radar system developed by NRL that might be of interest for insect research is a combination X-band (3 cm) and K_a-band (8.6 mm) radar. The X-band radar with 1° beamwidth is capable of high range resolution (0.5 m), and the K_a-band radar has a narrow 0.23° beamwidth that makes it attractive for low-angle tracking. This system is of relatively modest power. The two frequencies are radiated from separate antennas mounted one above the other. This system can possibly be made available for use. An improved version of this concept with higher power is the NRL TRAKX radar that combines simultaneous monopulse operation at K_a and X-bands from a single antenna.

Nike Hercules Radars

There are two radar systems that were part of the Nike Hercules systems that have been available as surplus. One is the X-band monopulse tracker that uses an 8 ft diameter antenna with a 250 kw peak power magnetron. The other is a K_a-band (2 cm) target-ranging radar with peak power of perhaps 125 kw. These radars, with slight modifications, make suitable experimental systems.

AN/MPQ-4

This is a unique radar originally designed and used as a mortar-located radar. Since it is being replaced it could become available as surplus for applications such as insect research. It is a high power X-band equipment with two narrow pencil beams at two elevation angles that perform a rapid sector scan over a limited azimuth angle. These radars have been used by the army for the investigation of insects. It should be seriously considered as a candidate radar.

WX-50

This is a K_a-band (8.6 mm) radar built by Westinghouse for airborne operation. It has a peak power of 100 kw, a 1.5° antenna beamwidth, and a 0.1 μs pulsewidth. It is designed for light weight (140 lb) and low cost. (Production cost in quantity is estimated at $70,000. per copy.) It is, however, of short range. A more capable radar manufactured by the same company is the X-band radar for the F-16 aircraft. For insect research, the small airborne antennas could be replaced with larger apertures.

Airborne Weather Radar

These are X-band radars of modest range capability, but are of interest for insect research because of their availability and relatively low cost. They are generally of low power (20 kw peak, 20 w average).

AN/TPN-25

This is an Air Force Precision Approach Radar (PAR) that operates at X-band. It is mentioned here because of its unique ability to rapidly scan (at a 0.5 s data rate) a two-dimensional sector (15° by 20°) with a narrow (0.75° by 1.40°) pencil beam. It can track six selected targets at a rate of 20 looks per second. The peak power is 320 kw and average power is 1 kw. It has a 20 nmi detection range on a T-33 aircraft target.

NOSC FM-CW Tropospheric Radar Sounder

This is an S-band (10 cm) radar developed by Dr. Jergen Richter of NOSC, San Diego, for the probing of weak atmospheric effects including the detection of insects. It is a transportable radar capable of 2 m range resolution. It was designed as a research tool and should be considered as a possible candidate for insect research.

Millimeter-Wave Radar

The window at 94 GHz (3 mm) might be used for millimeter-wave radar. There are no operational radars at this frequency, but there have been experimental radars of relatively short range built here. One example is a portable van-mounted radar built by the Naval Air Development Center. Its average power was less than one watt. This radar has been used for research purposes by many organizations and might be available on loan for insect research. A dedicated radar at 94 GHz might have about a 10 nmi range on a 1-square meter target, limited primarily by the large atmospheric attenuation experienced at these frequencies.

Frequency and Polarization Diversity

A radar with sufficient frequency diversity to test the scattering behavior of insect echoes as a function of frequency is a desirable research feature. To cover the frequency range that will probably be desired requires multiple radar systems and, therefore, it is an expensive capability. Polarization diversity, however, can usually be accommodated with most antennas at a modest cost.

Dedicated Radars

As far as is known, no one has published the characteristics of a radar specially designed and dedicated to insect research. This should prove to be an interesting exercise. Fixed ground-based, portable ground-based, and airborne radar should all be considered.

General

There are several approaches to acquiring a suitable radar for insect research. These may be listed as:

1. Use of an existing operational radar on an existing site on a not-to-interfere basis. This is probably the simplest and cheapest approach, but lacks flexibility.

2. Purchase an existing radar off someone's production line and modify it for insect research. This is apt to be an expensive approach, and probably is limited to small radars. One of the modifications that can be made at relatively small expense to improve performance is to purchase separately a large antenna.

3. Acquire a military radar declared surplus and modify accordingly. This is probably the cheapest method of obtaining a high-performance radar.

4. Borrow an existing radar experimentally developed for similar research purposes.

5. Design and develop a dedicated radar to meet the special demands of insect research. This is the most expensive approach, but it is the approach most likely to achieve what is desired.

Table I. RADAR MEASUREMENT CAPABILITY

Range
- About 100 meters accuracy can be expected as typical out to the maximum range of the radar. Accuracy of a 0.1 meter is possible, limited only by the accuracy with which the velocity of propagation is known. The range of a radar is fundamentally limited by the line of sight rather than by sensitivity. For ground-based radars this is of the order of 10 miles (actually depends on the radar height) against near-surface targets.

Angle
- Beamwidth of one degree is typical, as small as 0.2 degree is possible. Angle accuracy of one-tenth beamwidth is achievable, with a practical limit of 0.1 mil.

Range Rate
- Relative velocity of a fraction of a meter/sec is possible. Doppler frequency shift is used more to separate moving targets from stationary clutter rather than for the measurement of relative velocity, (except for extraterrestrial targets where Doppler is used for extracting relative velocity).

Data Rates
- Mechanically rotating radars have typical data rates of 5 to 15 rpm, but can be as fast as 300 rpm or greater. Phased array data rates can be equal to the pulse repetition frequency. Some mechanically scanned antennas can cover a limited angle sector at a rate of 10 scans/sec or so.

Target Capacity
- Target handling capability limited only by the ability of an operator or the capacity of a computer. Automatic tracking of as many as 500 individual targets is practical. Nonresolvable targets can be tracked as a "cloud."

Size
- Target sizes can be measured to a fraction of a meter accuracy if there is sufficient signal-to-noise to define the extremities of the target.

Shape (Image)
- Synthetic aperture radars are capable of imaging a target or mapping the ground with a resolution comparable to that achievable with a range measurement alone. Resolution better than 3 m is possible. Polarization provides a measure of the target symmetry.

Recognition
- Targets such as aircraft, ships, and satellites can be separated by class on the basis of radar measurements. Surface features such as crops, ice, sea state, and geological features can also be recognized. Some species of birds can be differentiated from others by radar.

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"TYPICAL" RADAR CHARACTERISTICS*

(As might be considered for insect research)

Frequency: 10,000 MHz, 3 cm wavelength, X-band --- (5 cm to 3 mm)

Pulse width: 1 μs, 150 m resolution --- (1 ns to 10 μs)

Pulse repetition frequency: 2000 Hz, 75 km unambiguous, range --- (200 to 10,000 Hz)

Peak power: 250 kw --- (50 kw to 1 mw)

Average power: 500 w --- (50 w to 10 kw)

Antenna beamwidth: 1° --- (2° to 0.2°)

Antenna size: 8 ft --- (3 ft to 30 ft)

Range on insect targets: A few kilometers to 100 km

* Range of characteristics not necessarily self-consistent.

SOME FORMULAS USED IN RADAR

Unambiguous Range:

$$R_u = \frac{c}{2f_p} = \frac{1.5 \times 10^8}{f_p \ (Hz)} \quad \text{meters}$$

f_p = pulse repetition frequency

Gain of an Antenna:

$$G = \frac{4\pi A \rho}{\lambda^2}$$

A = physical area

ρ = efficiency (typically = 0.6)

λ = wavelength

$$G \approx \frac{20,000}{\theta_a \theta_e}$$

θ_a, θ_e = beamwidths (degrees) in azimuth and elevation planes

Antenna Beamwidth:

$$\theta_B \approx \frac{65\lambda}{D} \quad \text{(degrees)}$$

D = aperture dimension

Peak and Average Power:

$$\frac{P_{av}}{P_t} = \tau f_p = \text{duty cycle}$$

τ = pulse width

Doppler Frequency Shift:

$$f_d = \frac{2v \cos\theta}{\lambda} = \frac{2v_r}{\lambda}$$

$$f_d(Hz) \approx \frac{V_r \text{ (knots)}}{\lambda \text{ (meters)}}$$

v = velocity of target

θ = angle between radar ray and target vector velocity

v_r = relative velocity

Number of Hits Received from a Target, With a Rotating Antenna:

$$n_B = \frac{\theta_B \, f_p}{6 \, \omega_m}$$

θ_B = azimuth beamwidth (degrees)

ω_m = antenna rotation rate (rpm)

Distance to the Radar Horizon:

$$d \text{ (n mi)} = 1.23 \; (\sqrt{h_a} + \sqrt{h_t} \;)$$

h_a, h_t = antenna height and target height, in feet

Measurement Accuracy (Theoretical rms Error):

$$\text{Range:} \quad \delta R = \frac{c}{2} \times \frac{t_r}{2(2S/N)^{\frac{1}{2}}}$$

c = velocity of propagation

t_r = rise time of pulse $\approx \frac{1}{B}$, B = bandwidth

S/N= signal-to-noise ratio

$$\text{Angle:} \quad \delta\theta = \frac{\theta_B}{(2S/N)^{\frac{1}{2}}}$$

Radar Letter Nomenclature:

Letter	"Nominal" Wavelength	Letter	"Nominal Wavelength
L	23 cm	K_u	2 cm
S	10 cm	K_a	8.6 mm
C	5 cm	mm	3.2 mm
X	3 cm		

APPENDIX II

AMPLITUDE FLUCTUATIONS EXPECTED FROM A DISTRIBUTED TARGET

Consider a distributed cloud-like target D meters in diameter, such as might be produced by a convective cell or a swarm of insects. The antenna beamwidth and range are assumed to be such that the target cloud is larger than the resolution of the antenna. The angular backscatter pattern of such a target will consist of a lobed structure with angular separation between nulls of the lobes approximately equal to $\theta_\ell = \lambda/D$ as seen from the target, where λ = wavelength. The target is assumed to have random-like scattering centers so that its scattering pattern will also be somewhat random in nature. As the target moves relative to the radar, the backscatter echo seen by the radar will be amplitude modulated because of the change in the position of the scattering lobes. (A distributed target such as a convective cell or a swarm of insects might change its physical configuration with time which will also contribute to a varying cross-section. However, the fluctuations due to this effect will be ignored here. As seen from the target the rate of change with time of the angle ϕ measured between the radar and the perpendicular to the target trajectory is

$$\frac{d\phi}{dt} = \frac{v_t}{R} \cos \phi$$

where v_t = target velocity and R is the range to the target. The time between nulls of the scattering pattern is then $\theta_\ell/(d\phi/dt)$. The rate at which the amplitude of the echo fluctuates is the inverse of this, or

$$f_a = \frac{d\phi/dt}{\theta_\ell} = \frac{v_t\, D}{R\, \lambda} \cos \phi$$

Consider the following numerical example: v_t = 10 m/s (20 knots), antenna beamwidth = 1.5°, R = 5 km, λ = 3 cm, and ϕ = 0°. The diameter D is Rθ = 125 m. The frequency of the amplitude fluctuations is calculated to be 8.3 Hz, which is within the range of that previously observed from insects. In the above case, the target was assumed to move perpendicular to the radar line of sight. When the target moves parallel to the line of sight, the amplitude fluctuation is essentially zero.

The amplitude fluctuations due to a moving distributed target can in principle be distinguished from the insect wingbeat frequency since the former will vary with the relative velocity of the swarm; that is, with direction of view and speed. The wingbeat frequency should not be so dependent. Thus a simple test ought to be able to tell if the wingbeat frequency is useful for target recognition. (However, if the fluctuations are actually due to the internal motions of the cloud, the test will fail.)

This analysis is only approximate. It is included to show the magnitude of the effect and is not meant to be a complete treatment of the problem.

POSSIBLE IMPACT OF RADAR ON PEST MANAGEMENT OPERATIONS

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I would like to begin by expressing both my appreciation to those concerned at the USDA and NASA for the invitation to attend such a timely workshop at such a historic estab lishment, and my special thanks to all concerned in New Brunswick, Canada; my contribution here today arises, in particular, from the four seasons of field research to observe spruce budworm moth flights (following earlier similar work in the Sudan) with radar which were undertaken jointly by the Canadian Forestry Service and the New Brunswick Department of Natural Resources, co-ordinated by Dave Greenbank, and in which I have been privileged to participate. Finally, it has been Forest Protection Ltd., an operating agency of government and industry in New Brunswick, which has enabled me to attend this workshop.

IMMEDIATE APPLICATIONS TO CRUCIAL PROBLEMS

In response to the organizers' invitation "to provide some vision of the role of radar in pest management operations," I think the clearest vision is provided by concentrating on some immediate and possible further applications of existing and fully field-tested equipment and techniques for doing some things which badly need doing and that only radar can do. Radar provides a unique means of making and maintaining contact with important populations of major pests at a stage and at times when they may otherwise be largely or even wholly overlooked in flight. Dr. Knipling (1977), in his presidential address to the 14th International Entomological Congress in Canberra, pointed out how we as entomologists have collectively underestimated the flight range of virtually all insect pests.

For some of the most serious third-world pests, such as the desert locust (*Schistocerca gregaria* - Orthoptera: Acrididae) and the African armyworm (*Spodoptera exempta* - Lepidoptera: Noctuidae), complete loss of contact with the main populations for months at a time are now the outstanding problems in the development of more effective control. In the future control of such pests, the operational introduction of the radar techniques that are now available may prove, in my view, to be the most significant development since the deployment of the synthetic insecticides.

Evidence in support of this possibly rash-sounding claim is available for these species, as well as for Sahel plague grasshoppers (particularly *Oedaleus senegalensis*). In the verbal presentation of this paper, time permitted dealing with only one of these, the desert locust. Although much of the subsequent workshop proceedings proved to focus on the fall armyworm (*Spodoptera frugiperda*), the North American counterpart (ecologically as well as taxonomically) of the Old World *Spodoptera exempta*, the corresponding evidence of the scope, need, and probably crucial importance of radar for the improved control of the latter species will also be outlined.

DESERT LOCUST

The desert locust, from the time of Pharaoh until the current upsurge, of which I saw a sobering sample on the Red Sea coast of Yemen last February, remains one of the most formidable problems of pest management in more than forty countries of Africa and the Near East, from Bangladesh to the Atlantic and from Tanzania to Turkey and Turkmenia. By the early 1960s it was admittedly possible to conclude cautiously that specially developed ultra-low volume spraying techniques and materials, applied on unprecedented scales, were beginning to measure up to the size of the collective job, assessed as orders of magnitude of numbers of locusts to be killed, relative to the numbers of toxic doses being applied and to quantitative field evidence on efficiencies of application. But the maximum collective control effort then achieved, though probably contributing very significantly to the collapse of the plague between 1960 and 1962, made demands on personnel and resources, both national and international, much too great to be reasonably sustained indefinitely.

The scale of potential crop loss, and in part the magnitude of the control problem, arises from the biomass involved, which for a single large swarm amounts to tens of thousands of tons with a daily food intake of similar mass. But a still more formidable element of the desert locust control problem is the mobility of the pest. This was vividly illustrated by the swarms that originated in northern Arabia during the 1968 upsurge (Waloff, in preparation) and that subsequently crossed the Red Sea and almost the maximum width of Africa (through Egypt, Sudan, Niger, southern Algeria, and Mali) to Mauritania - some five thousand kilometers in less than two months.

The crucial problem of long-term control of the desert locust has indeed become that of the successions of months during which all contact is lost with the mobile and elusive remaining populations of the species, particularly over the deserts and their fringes. The very precisely downwind direction of displacement of the flying swarms, and their consequent accumulation into zones of low-level wind convergence, such as the Intertropical

Front, has long been established (Rainey, 1951, 1963, 1978a) - and, because low-level wind convergence is an essential (though not sufficient) condition for rain, incidentally representing the main survival value of this flight behavior. Some ten years ago it was suggested (Joyce, 1968) that improved control of the desert locust - and of some other major insect pests - was essentially a problem for aircraft with search radar and Doppler radar wind-finding equipment. Almost at the same time Schaefer (1969, 1976), with his ground-based radar in the Sahara, was duly observing scattered night-flying locusts flying rapidly downwind and becoming concentrated at wind-shift lines. Since then, examples have multiplied of situations where, with hindsight, the Intertropical Front ('e.g., across the uninhabited areas of northern Sudan in June - September 1967) was in all probability exactly the right place to have looked for crucially important and temporarily missing desert locust populations (Rainey, 1973). Back in July 1971, my colleagues made use of the daytime sea-breeze front of southern England for a training exercise to test the Doppler-equipped Pilatus Porter from Vernon Joyce's Agricultural Aviation Research Unit for locating, exploring, and sampling the insect concentrations of this front. This exercise enabled them to do just these same things by night with the same aircraft in the kinematically very similar Intertropical Front in the Sudan three months later (Haggis and Harness, in Rainey 1976). Five years later in New Brunswick, Canada, another sea-breeze front with a concentration of spruce budworm moths observed at the wind-shift by our DC-3's Doppler radar equipment (Greenbank, Schaefer & Rainey, in press), provided a similarly relevant model of what must surely be tomorrow's search-and-strike operations against the desert locust.

AFRICAN ARMYWORM

The African armyworm, *Spodoptera exempta*, is a major pest of cereals and grazing throughout southern and eastern Africa and southwestern Arabia, where (in particular in the Yemen Arab Republic, Ethiopia, Kenya, Tanzania, Malawi, Rhodesia and South Africa) its attacks attain from time to time the severity of major locust invasions. Most seasons start with new outbreaks of the characteristically high-density larvae which appear during October/December within some particular area of south-central Africa comprising Malawi and neighboring parts of southern Tanzania, Zambia, and Rhodesia. These come from entirely unknown sources, after a period of several months, with no infestation reported anywhere, and with resting stages virtually unknown in the species. From these first groups of outbreaks, successive generations can be recognized in most years (Brown, Betts & Rainey, 1969) extending both northwards, across Tanzania, Kenya, Uganda, Ethiopia, and sometimes as far as Sudan and Yemen, and southwards across Rhodesia and South Africa; in some years

there is fragmentary evidence of return movements southwards from Ethiopia and northwards from South Africa. These sequences of infestations are roughly comparable in seasonal regularity with those of *Spodoptera frugiperda* in North America, and geographically somewhat more extensive. In a manner rather similar to the desert locust, recognition of the degree of seasonal regularity, the scale of these *exempta* movements (up to some 3500 km in about eight months and about as many generations), and the severity of the damage (particularly heavy for example in 1977 in South Africa, Malawi, Tanzania, Kenya and Yemen) is now focusing attention on the crucial problem of locating the missing generations which provide the parents of those first reported infestations in October-December in south-central Africa (Rainey, 1978). As with the desert locust, this crucial problem appears to call specifically for the deployment of what may fairly be called the New Brunswick system.

Thus, the parent moths are known to be capable of flying for 12 hours or more at a stretch, probably often over distances of hundreds of kilometers, but largely, or wholly by night, and thus commonly overlooked. For more than a decade, however, these flights have been monitored by international networks of light-traps and more recently of pheromone traps, which give information on the night-by-night changes in the distributions of the moth populations; integrated into the information provided by the corresponding routine reports of the infestations of larvae, this has incidentally made possible a regular weekly forecast service which, since 1970, has been providing warnings of a substantial proportion of the infestations in Kenya, Tanzania, and Uganda in the right district and in the right week (Odiyo, 1974). More particularly, it has provided striking circumstantial evidence of accumulation and concentration of armyworm moths in semipermanent zones of low-level wind-convergence. This was demonstrated, for example, by the way in which hourly light-trap catches of this species in the Nairobi area were found (Haggis, 1971) to reach very high values (more than a thousand moths in an hour) at wind-shifts that represented surges of the African Rift Convergence Zone. This feature of the Africa wind-systems (known also as the Zaire Air Boundary) was found in 1970 to be readily located by the Doppler-equipped Porter aircraft already mentioned, and in Kenya one particular surge of this convergence zone, which had been found in this way, subsequently proved to have been associated with new armyworm attacks near Nakuru (Rainey and Joyce, 1972). The Zaire Air Boundary extends south-westward as a major weather feature affecting southern and western Tanzania, Malawi, Zambia and neighboring countries. In 1971 some of its surges (Bhalotra, 1973) were found to have been associated with the crucial first seasonal appearances of moths *S. exempta* in this area (Odiyo, 1972). Most regrettably, radar has never been used to observe this species; however, the systematic location and exploration of zones of wind-convergence, particularly the Zaire Air Boundary in this area and season, using a system similar to the New Brunswick aircraft equipped with the Cranfield/Schaefer insect-detecting radar, the Doppler wind-finding radar, and navigation system, appears to be a technical necessity if a maximum effort is to be made against this pest.

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RADAR OBSERVATION OF INSECTS - MOSQUITOES

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ABSTRACT

For several years studies of insect behavior have been made with data obtained from a 16 GHz radar. Tests were conducted at several sites over the coastal lowlands of New Jersey and over a region of high plains and low mountains in Oklahoma. In one area, a salt marsh in New Jersey, extensive ground tests on insect numbers were run during periods of radar operation. These ground tests were combined with laboratory data on expected insect backscatter to arrive at an extremely convincing model of the insect origin of most "Dot Angels." The radar studies give a great deal of insight into the buildup and dispersal of insect swarms, since radar can "follow" insects where other. means of trapping and observation cannot. In particular, new data are available on large-scale behavior as a function of wind and topography.

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INTRODUCTION

"Dot Angels" have been observed for many years, and their contribution to radar clutter is well documented [1] - [4]. These airborne clutter returns become increasingly bothersome at higher frequencies. This paper reports on a program undertaken to evaluate degradation of radar performance and to ascertain the insect origin of these phenomena. These requirements were met by using a radar as a remote sensor of insect behavior. In particular, the early work (1969) at Fort Monmouth, New Jersey [5] showed an extremely close correlation with crepuscular insect (especially mosquito) activity; this in turn prompted further work in the extreme insect environment over Lower New York Bay. Since a literature search produced no data on mosquito returns at our radar frequency, 16 GHz, laboratory measurements were made [6] which were then extrapolated to expected radar returns [7] (these are consistent with work at longer wavelengths and with larger insects [8]). These, in turn, were used in comparing radar displays of mosquito-prolific New Jersey salt marshes with "Ground-Truth" based on insect trapping. These three New Jersey locations are shown in Figure 1. The radar was sited at the arrow point in each case. These points are each at the center of a circle showing the maximum radar range. The New York Bay/Sandy Hook location (top) has concentric circles of 10 kilometer and 15 kilometer radii. The longer range version of the radar was used in a second series of tests. The Fort Monmouth/Shark River location (center) and the Salt Marsh/Manahawkin Bay location (bottom) used the radar with 10 kilometer maximum range.

Additional data, taken at Fort Sill (Lawton), Oklahoma checked the consistency of the insect theory when extended from the coastal lowland to the Great Plains, Figure 2. Fort Sill is adjacent to and north of Lawton.

RADAR DISPLAY CHARACTERISTICS

The radar used in the program was the AN/MPQ-4 Mortar Locator. In normal operation, a narrow beam is mechanically scanned alternately across a lower and upper beam position. These beam positions fill the same arbitrary 24° (425 mil) azimuth angle and are separated by about 2° in elevation. Either or both beams may be presented on the range/azimuth/intensity or "B scope" display. This is illustrated in Figure 3 [9]. In this paper, only single beam data are reported. The full 24° azimuth coverage is always displayed. However, the range may be "full" or in 20% increments. The lower beam may be arbitrarily positioned from -5.625° (100 mil) to +11.25° (200 mil).

The next two figures compare the "B" display with photographs of the area illuminated by the radar. In addition they show how insect returns can mask other targets and illustrate insect - precipitation differences. Data were taken at Fort Sill. Figure 4 shows the radar display with light, medium, and heavy airborne clutter. This sequence proceeds clockwise from the photograph of the water tower. This water tower, plus some associate structures, appears as the target echo near the center of each of these radar displays. These are in a northerly direction about one mile from the radar site. The photograph of the water tower also shows the lush grass in the foreground. The spring had been extremely wet and in normal years this grass would have dried out well before the date of the photograph (May 16). The medium and heavy clutter situation were recorded, respectively, at 2100 and 2226 on May 16. (All times of this report are CDT.) Sunset was at 2021 and this increase was typical of the after-sunset buildup observed in similar, extremely hot and humid evenings in the Atlantic coastal area. A similar buildup had been observed at Fort Sill during daytime operations, and increased activity corresponds to increasing temperature. The light clutter situation was recorded at 1300 on the following day. We were plagued by an extreme number of mosquitoes, most of them enormous, during this evening of very high radar clutter. We captured 3 insects intact, and these were later identified as 2 *Psorophora ciliata* and 1 *Aedes nigromaculis*.[1] It is interesting to note that the *Psorophoro* is far larger than the *Culex pipiens* for which the 1 km single insect range for this radar was calculated [6], [7]. The *Aedes* probably blew in from several miles to the south where there are abundant slickspots [10]. These radar displays are all in a mode showing a maximum range of about 2.3 miles (3.7 km).

Figure 5 is shown as an example of a different type of clutter; clutter of obvious meteorological origin (these data were taken with a display of about ten miles (16 km) in range). This is due to condensed moisture which was in the clouds but did not reach the ground. This area of the radar display was clear at the lower elevations. There is, however, some airborne biological clutter along the bottom of the radar displays. This comparison of clutter type can also be made by comparing this figure with the subsequent figures where the insects appear at greater ranges. The radar displays are presented with corresponding photographs of the cloud cover. The radar beam was at maximum elevation, 200 mils (11.25°), and slices the photographs about half way between the horizon and the top of the photograph. The left hand data were taken in a northerly direction and show the water tower of Figure 3. All data were taken at about 2008, 40 minutes before sunset on June 27.

[1]R. Ostergaard, private communication

TEMPERATURE EFFECTS

It was not difficult to separate temperature effects from other factors. Figure 6 gives an extreme example of the variation in insect activity with temperature. The two exposures show maximum return on each of two succeeding days, April 26 and 27, 1970, and with identical radar settings. The radar was at Fort Monmouth. The day to day temperature drop corresponds to a decrease in activity from moderate to low. The displayed range was 10 km.

GROUND-TRUTH, CREPUSCULAR BUILDUP AND SWARMING

Extensive radar data were taken and the results compared with actual insect catches in the summers of 1970 and 1971 at a site on the tidal marshes about one kilometer inland from Manahawkin Bay in Ocean County, New Jersey. The radar was placed on a bridge, locally known as "The Bridge That Goes Nowhere," which is reached from a northwesterly direction by a straight, well-graveled road. Figure 7 shows the radar emplaced on this bridge. The photograph also shows a "boat trap" headed upstream. A map of the area is shown in Figure 8 [11]. A bend in the road and tree line of low hardwoods are about 1500 meters along the road from the bridge. The tidal salt marsh extends at least one kilometer in all directions except toward the east, where a small arm of the bay, Turtle Cove, comes to about 600 meters from the radar location. Beyond the bay, a narrow barrier beach, Long Beach Island, forms the margin of the Atlantic Ocean. Minimum range to the ocean is about 4500 meters. The angular measurements were rather arbitrary, being based on an excellent boresight on a tower at the Barnegat exit of the Garden State Parkway, a distance of 9750 meters, or very nearly the maximum range displayed on the particular radar. The major insect observed is *Aedes solicitans*, the rather infamous Jersey salt marsh mosquito. These insects emerge from the marsh at fairly predictable periods, determined primarily by the lunar high tides. Operation periods were usually planned to observe various portions of this fortnightly cycle. This map shows artifacts outlining the history of mosquito control in the area. The oldest structures that appear to be drainage canals were actually dug so that predatory fish could find access to mosquito breeding areas. Subsequently, the circular pools were dug fairly deep, so that fish could remain in the marsh. Another principal current control is larviciding by helicopter. Figure 9 shows a photograph of a truck trap used to gather insect samples for ground-truth. This view is taken from the radar on the bridge looking along the access road, which is at 6140 mils azimuth. This is one of several roads used by truck traps for frequent mosquito sampling during

the warm months. Arrangements were made with the Ocean County Mosquito Exterminating Commission to sample this road every ten or fifteen minutes whenever the radar returns were particularly interesting. Insect catches (truck and others) were sent to the Commission's headquarters, where the mosquitoes were separated and catalogued and the non-mosquito remnants were sent to Rutgers University (1970) or the Monmouth County Mosquito Exterminating Commission headquarters (1971), where they were catalogued as to number and size. Those insect data (both mosquito and non-mosquito) were used to arrive at reasonable returns from insects [5], [7]. Since the frontal area of the vehicle mounted net or trap is about .5 meter^2 and since runs (round trip) were in excess of two kilometers, insects were sampled in a volume of about 10^3 meters^3. A count of a thousand mosquitoes was typical for the more active periods giving one insect per cubic meter. Now at a distance of one kilometer, the radar's resolution cell is on the order of 5×10^3 cm^3. Most radar data were taken with a somewhat elevated beam, so the density may have been somewhat lower; however, it does follow that even at this maximum range for a single mosquito, mosquito returns of from 2 or 3 orders of magnitude above minimum detectable return should not be expected.

In addition to the truck trap, a helicopter trap [5] was used in 1970 and a boat trap was used in 1971. Both of these were basically truck traps transferred to other vehicles. The airborne trap proved extremely unwieldy with the larviciding helicopter and had to be given up after a few fairly successful runs. The boat trap was mounted on a thirteen foot "Boston Whaler" with an eighteen horsepower outboard motor. It was operated, again on demand of the radar operator, along the canal parallel to the road and in other waterways throughout the area. When operating on parallel road and canal, the truck and boat trap ran as close together (in range) as feasible.

Figure 10 compares the radar returns with weighted truck and boat trappings for the — evening of August 3, 1971. Both sets show the generally seen crepuscular buildup, peaking by an hour after sunset. The first radar display, 2008 hours, shows mostly vegetation, particularly trees, from about one kilometer out on the left and a power line at the bottom center. This power line is also clearly visible along the road in Figure 9. The individual returns are from poles plus associated hardware. The several returns showing greater azimuths to the right are from guywires running over the road to poles which were further guyed out beyond the canal. Thus, this sequence of artifacts delineated the road. The second photograph was taken near the peak of the insect catches. There is a great deal of light return over much of the photograph and two distinct heavy bands which, except for the region over the road, go all the way across the radar display. This phenomenon is explained by species dependent swarming behavior. At the peak, 2030 hours, the truck trap gave a count of about 10^2 Chironomidae midges, to which our model gives a radar weight of 3.5 (Appendix II). The remaining 6.5×10^2 expected return was almost entirely mosquitoes, radar weight of 1. This was not an especially heavy mosquito night.

The final photograph, 2120 hours, shows complete disappearance of the very intense swarm and a more diffuse insect return. The trapping runs terminated 2115 hours, when the boat trap was damaged by one of the across-the-canal guy wires.

LAYERING AND INDIVIDUAL DOT ANGEL MOTION OVER COASTAL LOWLANDS

Figure 11 shows concentration of Dot Angels into a thin layer [12] and uniform general motion (coupled to the wind) [2], [3]. The term "atmospheric plankton" [2] seems especially appropriate here. These data were taken between 2212 and 2245 hours EDT. Sunset was at 1925 hours and the usual crepuscular buildup peaked within the next hour. This layer formed somewhat later and persisted for at least two hours. Each of these photographs is a superposition of 10 "B-scope" exposures taken at 5-second intervals. The striated appearance is thus due to the sampled paths of objects in reasonably uniform motion. The motion was toward the observer and azimuthal motion nulled at about (from) 4400 mils during most of this observation period. The two upper photographs were taken with a 150 mil (8.4375°) antenna elevation and show a slant range of about 3.3 kilometers, which also gives a layer height of 500 meters. Many other similar photographs taken during this period, and at additional azimuth angles, consistently show the same result.

Correlated motion, with or without layering, has been observed at all sites reported here and layering, probably fortuitously, has been observed everywhere except over Lower New York Bay.

A gated range, azimuth/amplitude and time display [7] was added to the radar system for use in the second series of tests at Manahawkin (1971). Figure 12 gives an idealized picture of how the radar displays the real world on both the build-in "B" display (radar screen) and on the added range gated amplitude display (recording oscilloscope). In this case the upper beam illuminates a bird in flight and the lower beam points down the center of two lines of low vegetative clutter (trees will extend into the upper beam at the shorter ranges). Note that the bird motion appears as motion on the corresponding "B" display. The target motion through the range gate is permanently recorded on a paper roll by the "range" display. Ideally, there should be one line for each scan in the given beam. The most recent line (scan) is at the top of the paper. Figure 13 shows the concurrent use of "range" and "B" displays. The 4000 mil azimuth points the radar toward the mouth of the creek. The creek bends to the left as it flows into the bay at Bay side on Figure 8 and the return on Figure 13 centered at 2 kilometers is from vegetation on this further bank. These data were taken at 2304 EDT on August 2. Sunset was at 2010 hours EDT and was followed by a buildup dominated by larger (than mosquitoes) insects. This was also apparent from stronger intensity (B-scope) and amplitude (Visicorder) displays.

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The azimuth/amplitude display was run while the five exposures, with five second intervals, "B" display photograph was made and shows about five seconds of running time. The range gate was at 500 meters. These returns show some temporal structure but are generally windborne, as observed for larger insects [8]. Similar display pairs were recorded at several azimuths and it was determined that the wind nulled out at about (from) 0000 mils.

Figure 14 shows decidedly non-insect motion and is given for comparison. The radar was located at the Sandy Hook (Lower New York Bay) site, as shown in Figures 18 and 19. The intensity display and simultaneous azimuth/amplitude records are part of essentially continuous data begun at 1640 hours EDT on August 25, 1971. The "B" displays show an indentation of the bay into the peninsula. The arc along the top of these displays is the further shoreline. Near land is on the left of the foreground and sea clutter (speckled appearance) is on the right. The bright bar across the bottom is due to the transmitted pulse. The lower display shows a short bright bar somewhat beyond this artifact. The upper photograph, taken tens of seconds later, shows a similar but larger bar at 300 meters, the range setting. This return is in both cases from a mass of seagulls somewhat rudely disturbed from their resting place along the near shore. The sequence shows the "flock" moving up into the beam and out into and beyond the range gate. The returns were extremely strong and the data of this figure were taken with greatly reduced I.F. gain. The gulls were quite cooperative and we made several earlier trials at higher gains. Note that in comparison to the previous figure, the birds show more intense returns, greater amplitude modulation and purposeful (dispersive) flight.

MOTION AND AGGREGATION OVER ARID HILLS

So far this paper has dealt with radar observations over the low and relatively humid New Jersey Coast. It was clearly desirable to record comparable radar data from an area with different geographic and weather characteristics; and, therefore, two series of observations were made from Fort Sill, Oklahoma [13]. Fort Sill was chosen because one of our (Fort Monmouth's) radars was there for testing and experiencing difficulty with airborne clutter (Section II of this paper). The first of these series followed an un-usually wet spring: May 16-17, 1972, and the second: June 27-28, 1972 was made during the dry prairie summer. Fort Sill, Figure 15 [14], is largely in the Wichita Mountains. The radar site is at the lower right hand corner. The 0000 azimuth was chosen for bore-sighting on a convenient water tower and was very near to true north. This tower is also shown in Figures 4 and 5. Some daytime return, much of it birdlike, was recorded during both series and the diurnal variations included the twilight effects of the other loca-tions. This activity was more intense for the days of higher activity when additional

phenomena were also seen. In the first of these, motion in a cloud-like mass, Figure 16, was observed a little over half an hour after sunset on May 16. This was at greater height and distance than the usual crepuscular effect shown by the bright areas at the bottom of the display. Both photos show the "cloud" from radar data at an elevation of 50 mils (2.8°). Radar data at zero elevation is superimposed, lightly, to show ground relief. The first (lower) "B" display shows the "cloud" over the pass between Apache Ridge on the left and Medicine Ridge shown on the right of Figure 16. The second, taken ten minutes later, shows the "cloud" to have progressed over the pass and almost to Rabbit Hill. This motion corresponds to wind from the southwest and the origin of the clutter in a region of outwashes and "Slickspots" south of the Wichita Mountains [10]. The mosquito population was extraordinarily high in the evening and they caused a great deal of discomfort to the radar operators. The insects appeared to be present in two sizes and the smaller one was subsequently identified as *Aedes nigromaculis*.[1] This animal breeds only in saline areas such as slickspots prevalent to the southwest and this capture served to verify the insect origin of this large scale clutter with large scale motion.

The second additional phenomenon observed in the more humid series is seen in Figure 17. Here a composite picture is shown at the upper right. The "landmarks" used are at the lower left, elevation 36 mils (2°) and the "aerial clutter" is given at the upper left with an elevation of 50 mils (2.8°). Referring to Figure 15, the landmarks are: Mount Scott (the highest peak in the Wichita Mountains) at the extreme radar range on the extreme right, the peaks of the hills around Brush Canyon at the center right, and Signal Mountain at the center left. The elevated data shows an aggregation of returns 425 meters (1400 ft) directly above the floor of Brush Canyon, as shown in the composite display. We conjecture that this collection occurred because of favorable moisture conditions.

LARGE SCALE MOTION OVER WATER

The concept of the salt marsh mosquito (*Aedes solicitans*) as a migratory insect figured in the early interest which entomologists gave to this project. It was largely on the advice of two of these people[2] that observations were made of activity over Lower New York Bay. These were made from a site near the seaward end of Sandy Hook (Fort Hancock). Boresighting of 0000 azimuth was originally on a tower in Atlantic Highlands, but later the corresponding Verrazano Bridge angle of 2689 mils was used. North is approximately 2800 mils.

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[1]R. Ostergaard, private communication.

[2]R. Ostergaard and D. Jobbins, private communications.

The nights of September 10, (Figure 18) and September 11, (Figure 19) 1969, were particularly interesting. On September 10 the wind was blowing steadily from the northwest, about 2000 mils, at 8 to 15 knots. Figure 18 shows radar data at 1600 mils (almost into the wind) and in quadrature - 0000 mils, superimposed on a standard chart of the area [15]. The arrow lengths correspond to 4 kilometers. The land mass at the top, Staten Island, is at a minimum distance of 12 kilometers. The radar data were taken with earlier times toward the top. Corresponding data at each angle were taken with as little time lapse as possible. The radar was at 50 mils (2.8°) elevation. (Zero elevation gave excessive sea clutter.) Range marks are at 2 kilometer increments. The topmost photos were made at 1900 EDT, ten minutes before sunset. They show a few artifacts such as channel markers, but nothing airborne. (Since both directions are over water, it would not be expected that the usual twilight buildup would be observed until carried into range by the wind.) The second or middle displays were recorded at 2015 EDT. Here dense masses are beginning to appear and the more dense is toward the land mass from which the wind is blowing. The final data shown, bottom, were taken at about 2120 EDT and show a reversal in that the near quadrature direction shows high intensity at greater ranges than are seen looking into the wind. From this, it appears that the peak of activity had passed over the radar site. The data are explained by the usual diurnal insect buildup over the land mass and with this buildup observed downwind as a function of elapsed time and distance.

Figure 19 depicts a comparable situation on September 11. Here the wind is fairly steady from the south. This, however, is based on motion as observed in the radar data and not direct reports of the local Coast Guard Station, as on the previous night. The two quadrature arrows of 4 kilometer length look generally into the wind, but here direction is of greater importance than relative wind speed. The first (top) radar displays were made at 1930 EDT, some twenty minutes after sunset. In the direction over land (4800) the usual crepuscular buildup has already peaked. Over water (0000) only slight clutter can be seen in addition to the artifacts presented in Figure 18 half an hour earlier on the previous day. The second, middle sets of radar data were made at 2000 hours. The overland direction shows a slight decline and buildup is seen to have occurred over water. The final photographs were made at about 2115 hours and both sets show decline. Modeling these data gives two insect sources, a close rather intense source from the lowlying woodlands of the peninsula and a more distant (minimum of 6 kilometers) and less intense source in the urbanized hills of the "Highlands."

CONCLUSIONS

The strong insect returns (angels), which occasionally plague the operation of microwave radars, become a distinct advantage when radars are used to study insect activity. Mobile "truck traps", "boat traps" and "helicopter traps" have been used to obtain insect counts which, when combined with data on the radar cross sections of small insects, verify the insect origin of most clear air airborne clutter detected by microwave radars. The temporal and special patterns of these returns both confirm and extend knowledge of insect behavior since the radar can "follow" swarms over such inaccessible places as over open water and over mountains.

Display techniques have been developed which show individual or small swarm motion within some larger cloud or mass, or which can show the overall motion over great distances. The influence of wind and terrain on insect motion and dispersal may now be determined from radar data.

ACKNOWLEDGMENTS

APPENDIX I

CHARACTERISTICS OF THE AN/MPQ-4A RADAR
(Table 1)

Maximum Range Displayed	
Early Data	10^4 meters, (6.2 mi)
Later Data	1.5×10^4 meters, (9.3 mi)
Maximum Range, $10^{-3}m^2$ Target	10^4 meters[a]
Maximum Range, $10^{-7}m^2$ Target	10^3 meters, (.62 mi)[b]
Horizontal Beam Width	17.8 mil, (1°)
Vertical Beam Width	14.25 mil, (.8°)
Azimuth Scan	445 mil, (25°)
Elevation Separation of (2) Sequential Azimuth Scans	± 35 mil, (±2°)
Scan Rate	17 per second
Radiated Frequency	16 GHz (Ku band)
Radiated Wavelength	18.75 mm
Peak Radiated Power	50 KW
Pulse Repetition Frequency	
Early Data	8.6 KHz
Later Data	7 KHz
Radiated Pulse Width	$.25 \times 10^{-6}$ second
Range Increment Corresponding to Radiated Pulse Width	37.5 m, (125 ft)

[a]This figure is quite conservative.

[b]This figure is based on the line above and the conventional 4th power radar range scaling law.

SCALING INSECT SIZE AND RADAR (AN/MPQ-4A) RETURNS

Earlier workers in radar entomology studied rather large insects at wavelengths of 30 mm and longer [4], [8], [16]. Using their data would have required extrapolation to the much smaller mosquitoes, which are of most frequent occurrence and greatest interest, and to a wavelength of 18.75 mm. Since the double extrapolation was unduly risky, fundamental measurements on mosquito returns were done in the Radar Technical Area at Fort Monmouth. It should be pointed out, however, that the results are consistent with those of other researchers. The technique is described below.

Voltage Standing Wave measurements of several rehumidified dead mosquitoes, live *Culex pipiens*, and accurately sized metal spheres were used to determine corresponding reflection coefficients (ρ). These measurements were made with the standard slotted line techniques at 16 GHz [6], the discontinuities, spheres or insects, being mounted in the center of the guide on polyfoam supports.

Figure 20 shows how the expected radar returns were interpolated from results for the metal spheres. The nomograph is a straight line as the data points all lie close to the Rayleigh region asymptote. We see that the typical expected, weighted, radar returns are equivalent to a metal sphere with a cross-section πr^2 of $10^{-6} m^2$. However, these insect returns were made with the mosquitoes in the most favorable alignment. Consequently, we arbitrarily use the figure of $10^{-7} m^2$ as being more typical. This is probably too conservative but is the number used throughout the program.

In Figure 21 the $10^{-7} m^2$ mosquito "area" and the $10^{-7} m^2$ cross-section for conducting spheres are both normalized to 1. The smooth curve is the classical radar response for the spherical metal targets at the radar frequency of 16 GHz. The histogram is averaged over insects of various lengths, e.g., from 4.5 mm to 5.5 mm for mosquito counts, scaled to the same law. Because the finite variation of insect lengths smooths out most of the fluctuations in the resonance region, only three sample sizes; 5.5 - 7 mm, 7-9 mm, and 9-12 mm, lie somewhat off (and slightly above) the corresponding optical branch. It should be noted that this figure gives expected radar returns as a function of target size, whereas the usual description [17], [18], gives the variation with the radius-wavelength ratio; the actual physical size of the target being suppressed. Thus these references show a constant return to the optical region and 4th power law in the Rayleigh region. It is obvious that, by definition, return is proportional to area (radius^2 for spheres, length^2 for insects) in the optical region and similarly the Rayleigh region is transformed from the 4th to 6th power. This gives the more directly useful curves plotted in this figure.

Table 2 gives the actual factors by which weighted insect counts were multiplied to give the estimated total radar return based on the single mosquito as the basic unit.

INSECT SIZE AND CORRESPONDING RADAR RETURN
(Table 2)

Physical Lengths (mm)	Relative Radar Return
1.5 - 2.5	.004
2.5 - 3.5	.047
3.5 - 4.5	.26
4.5 - 5.5	1.0
5.5 - 7	3.5
7 - 9	7
9 - 12	10
12 - 15	7
15 - 20	12
20 - 25	20

APPENDIX III

RADAR B SCOPE ASSAY

The cloud-like behavior of insect masses suggests the data be handled in some statistical fashion. There are a number of ways to do this operationally consistent with the form of all the other data. The technique is to prepare an overlay of little "boxes." Each box includes a small number of resolution cells mapped into the photograph of the radar display. Each box containing some target indication is given one count. This is similar to counting biological cells in extremely dilute solutions. Of course, extending the analogy, these are not dilute solutions. Those familiar with the radar art will also be aghast at the short shrift given to range effects; however, after a great deal of thought, we are convinced that these counts are monotonic with the actual returns. Figure 22 shows such a photo with two overlays, one of which is in position for the count. Most of the 1970 Manahawkin data were studied in this way and the results were a strong influence in the decision to continue the program.

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Figure 1. Radar locations in New Jersey.

Figure 2. Radar location in Oklahoma.
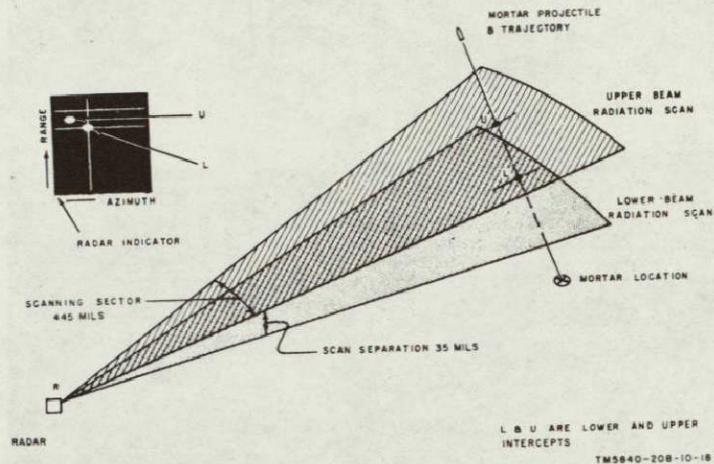
Figure 48. Scanning pattern for weapon location.
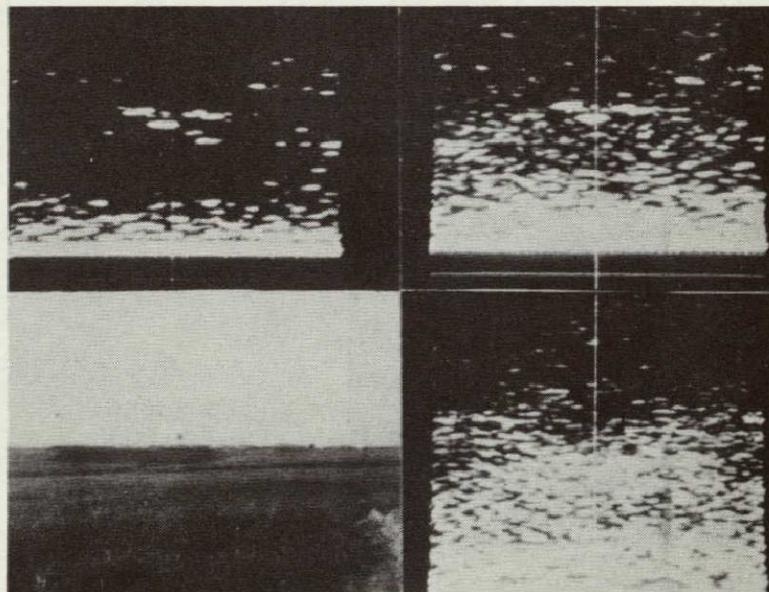
Figure 3. Radar scanning and display.

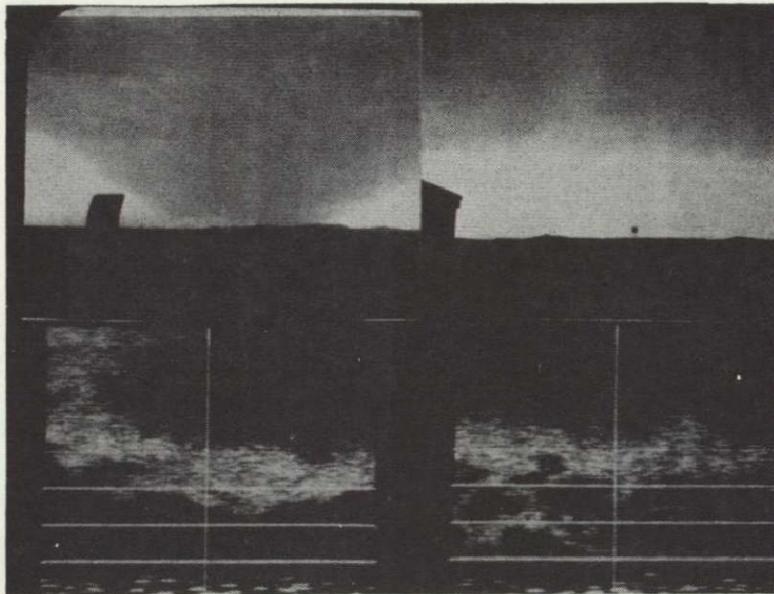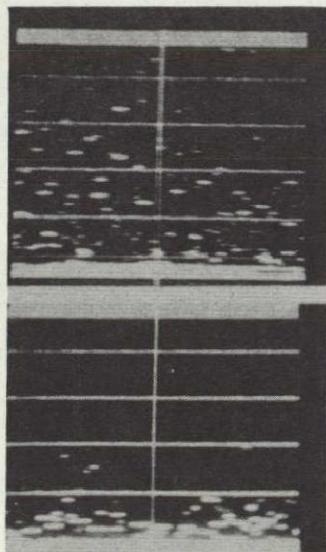Figure 4. Radar display of insect clutter.

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Figure 5. Radar display of weather clutter.

26 APRIL — 2037 — 62° F
S.S. — 1845
DAY'S HIGH — 1400 — 71° F

27 APRIL — 2020 — 54° F
S.S. — 1846
DAY'S HIGH — 0900 — 59° F

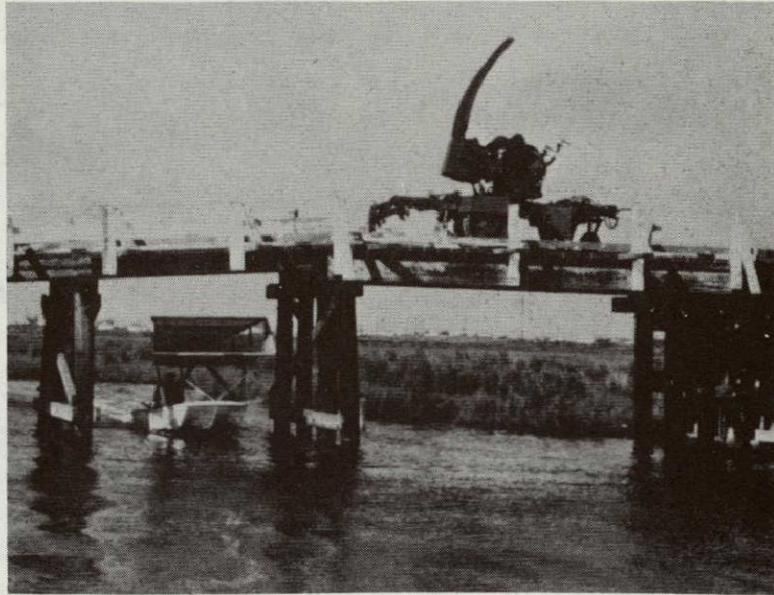Figure 6. Variation of insect returns with temperature.

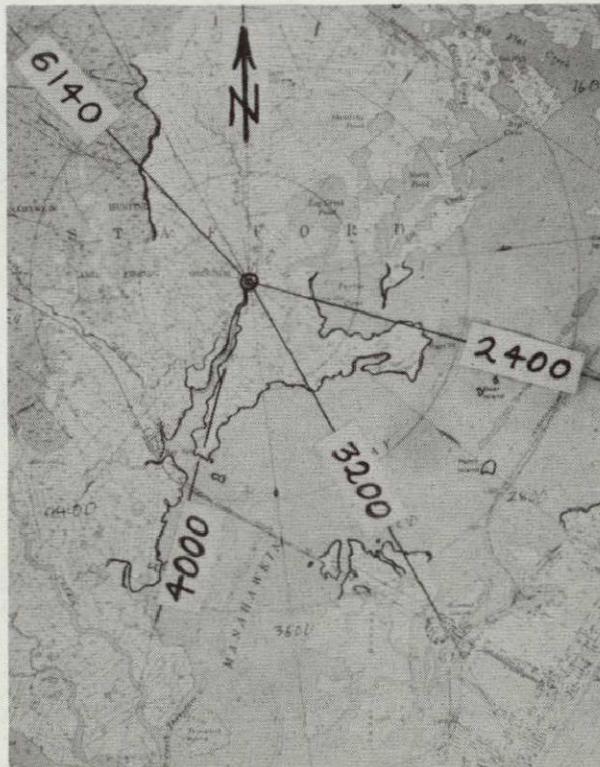Figure 7.   Radar and boat trap, Manahawkin, New Jersey.

Figure 8.   Map of Manahawkin area.

Figure 9. Truck trap, Manahawkin.

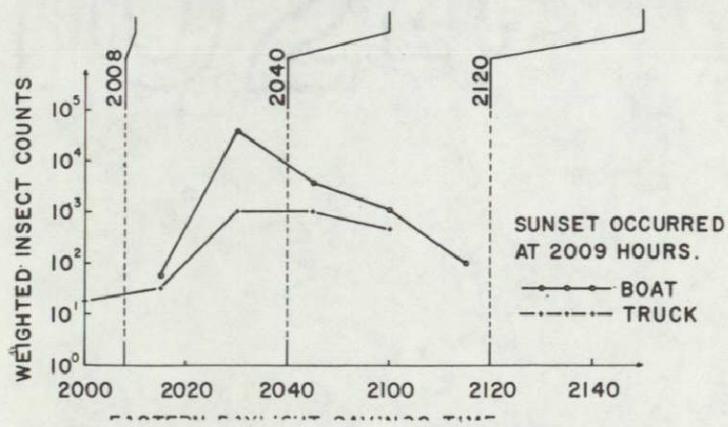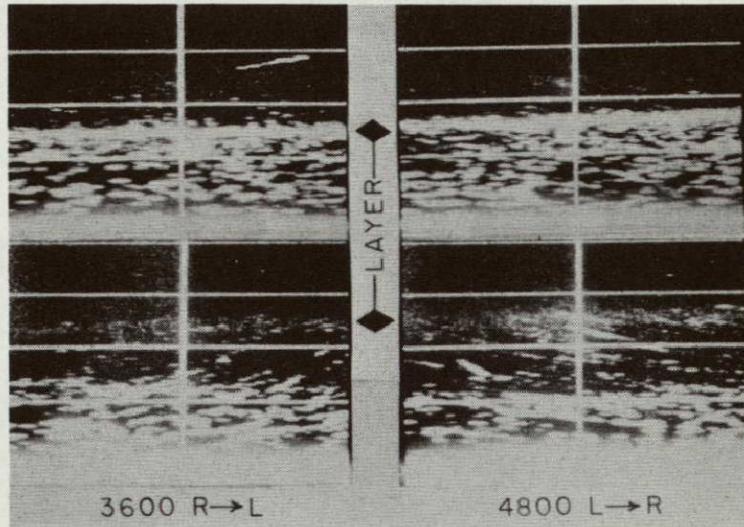Figure 10. Comparison of truck and boat trappings with radar display, Manahawkin.

3600 R→L   4800 L→R

Figure 11. Radar displays showing layering and wind drift, Manahawkin.

UPPER   LOWER

RANGE GATE   125'

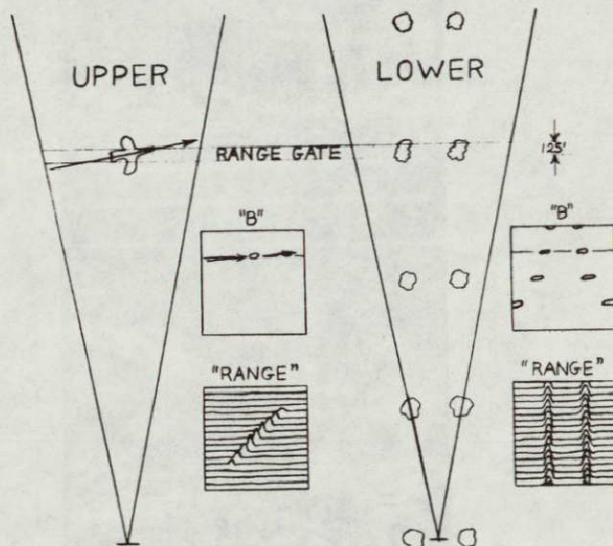"B"   "B"

"RANGE"   "RANGE"

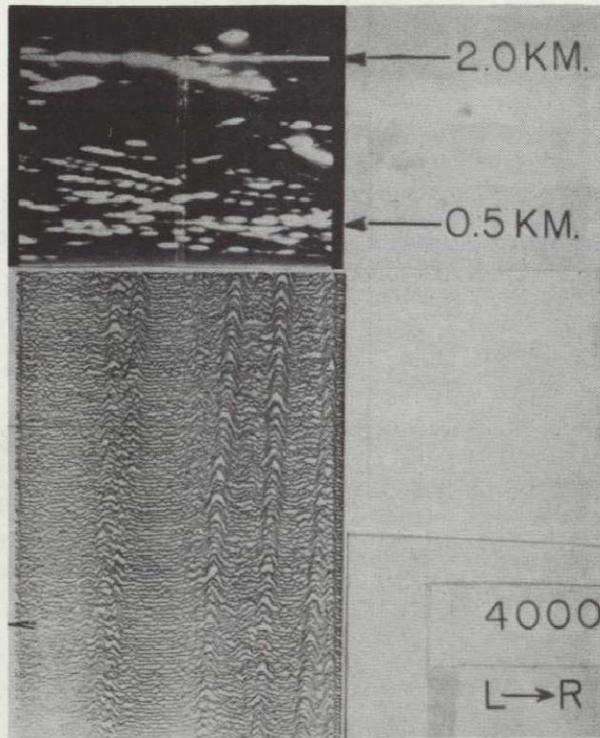Figure 12. Comparison of "B" and Range Gated Display.

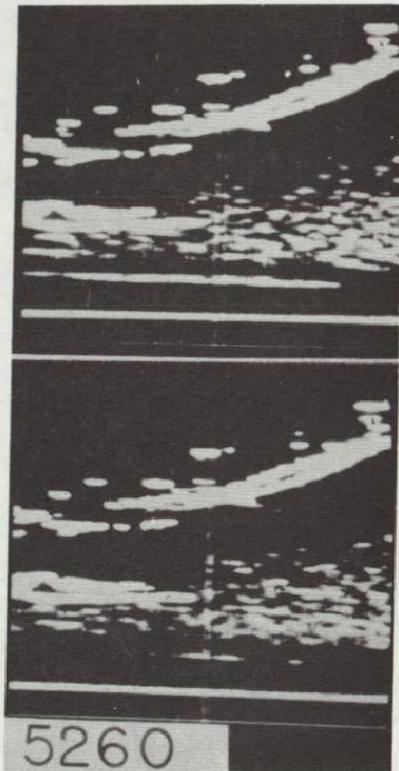Figure 13.   "B" and range gated display showing insect-like motion.

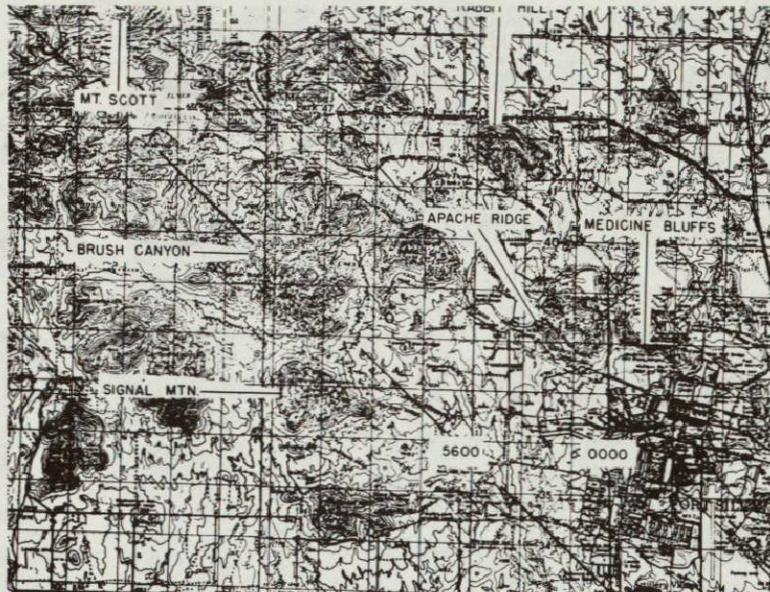Figure 14.   Range gated and "B" displays showing bird motion.

Figure 15. Map of Fort Sill.
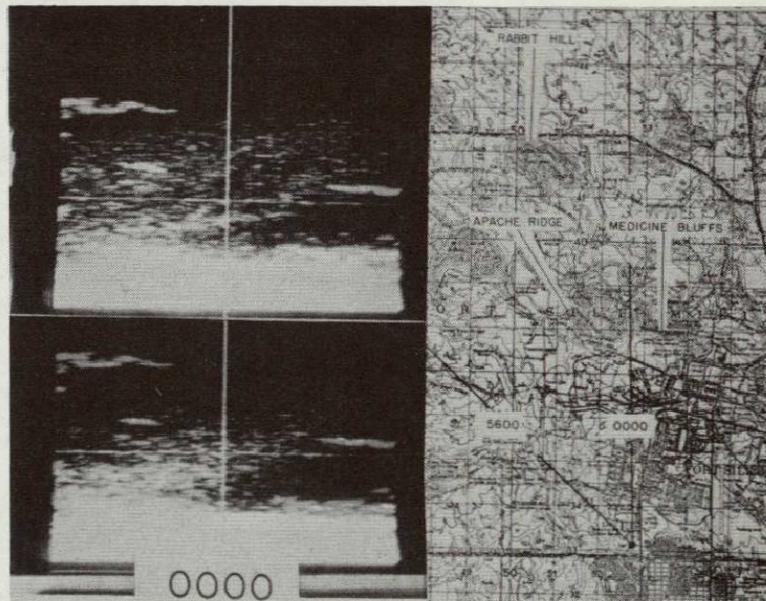
Figure 16. Cloud-like insect motion, Fort Sill.
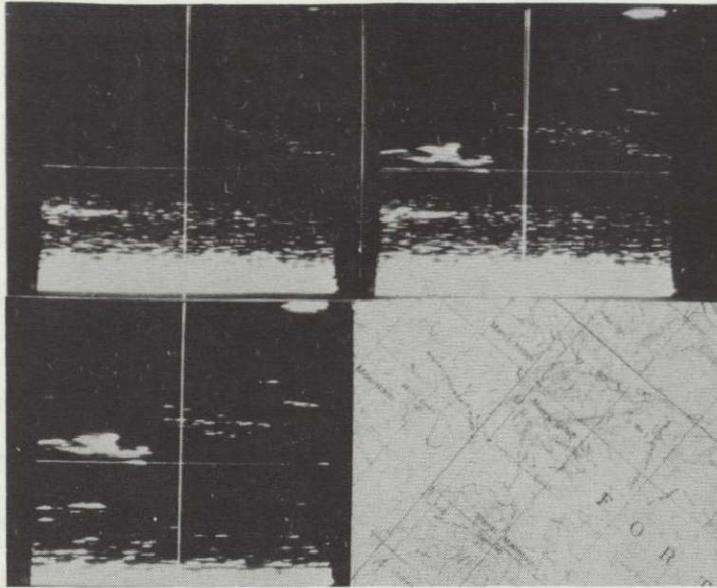
Figure 17. Localized insects, Fort Sill.

Figure 18. Insects from Staten Island observed at Sandy Hook, New Jersey.
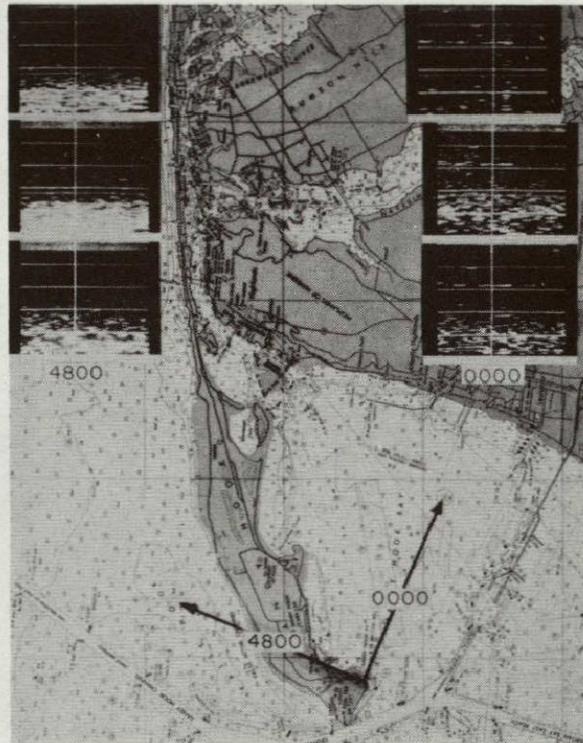
Figure 19. Insects from Northern New Jersey observed at Sandy Hook.
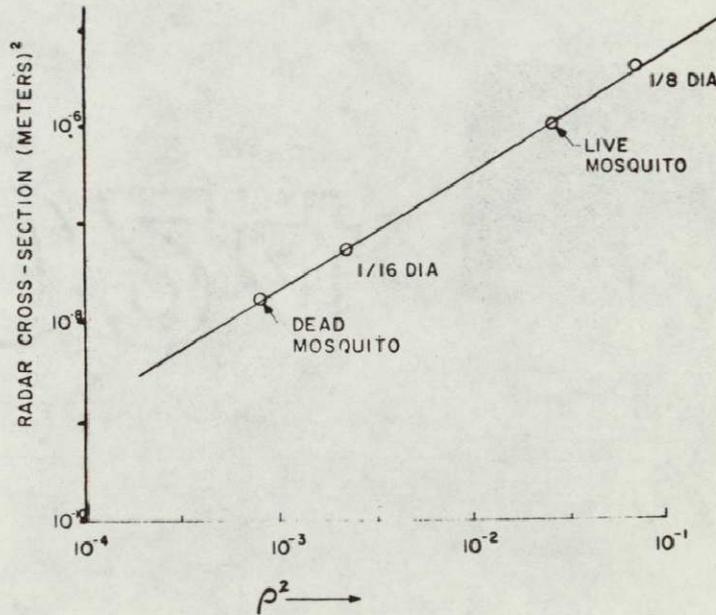
Figure 20. Waveguide measurements of Mosquito reflection coefficient at 16 GHz.

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Figure 21. Determination of relative insect cross section or "weight" as a function of body length.

NO. 46

12 AUGUST 1970

COUNT = 96 (OF 288)

AZ = 6140 MILS

EL. = 150 MILS

≈ 2005 EST

S.S. WAS 1901 EST

Figure 22. Grid used in radar - insect assay.

RADAR OBSERVATION OF KNOWN AND UNKNOWN CLEAR AIR ECHOES

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INTRODUCTION

Excluding superrefraction effects, there are two mechanisms which can produce radar echoes in the visually clear air. Either the echoes are from small targets 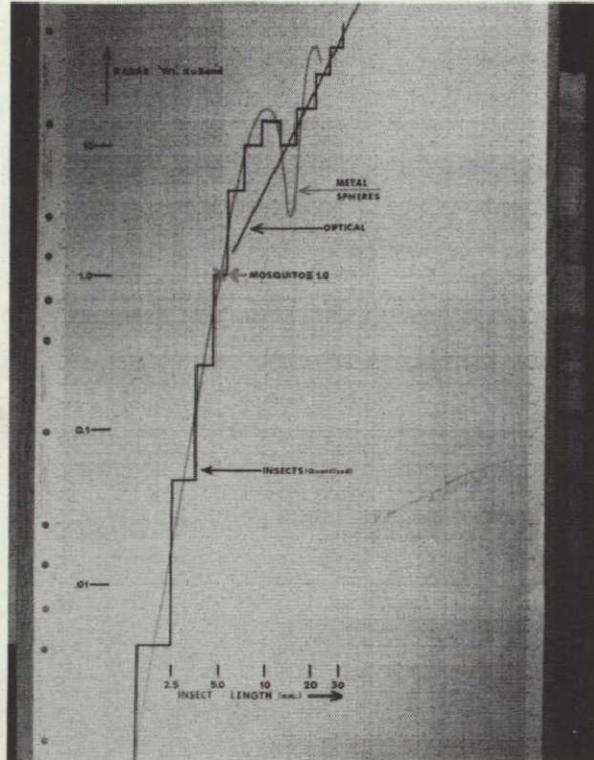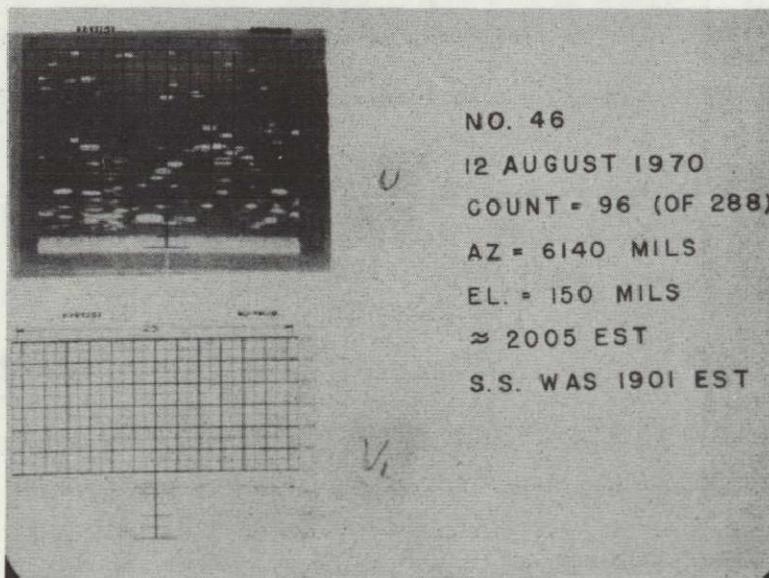such as insects and occasional birds which are invisible to the eye or there is sufficient scattering from refractive index inhomogeneities to be detectable. Early investigations of clear air radar phenomena demonstrated that relatively insensitive radars can detect insects at close range[1] and also predicted that refractive index inhomogeneities can provide a detectable radar return.[2] However, disagreements over the source of radar backscatter from regions of apparently clear atmosphere persisted in subsequent studies.[3,4] The problem was complicated by the fact that atmospheric structures such as convective bubbles, inversions, and fronts which may have refractivity gradients sufficiently sharp for backscatter are the very structures whose formation tends to concentrate particulate matter and insects. Moreover, the relative importance of one source of backscatter in a given series of measurements was usually clouded by the almost total lack of quantitative observations for either known insects or refractivity perturbations.

Beginning in 1965, a series of experiments by Air Force Cambridge Research Laboratories and the Applied Physics Laboratory personnel, using NASA's sensitive multi-wavelength radar facility at Wallops Island, Virginia, were successful in distinguishing backscatter from insects and birds from that of refractivity perturbations. Although

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* Formerly Air Force Cambridge Research Laboratories

accounts of these experiments, as given in References 5 through 9, preclude further de-
tailed description, a summary of these efforts may be of benefit to entomologists looking
toward radar as a potential investigative tool. In this paper, examples have been selected
from these early works to give entomologists some indication of the types of information
that are available by radar as well as examples of the different sources of clear-air
radar backscatter.

RADAR CHARACTERISTICS

Three high powered, high sensitivity radars of differing wavelengths were used in
these experiments. The characteristics of these systems are shown in Table 1. The radar
of 10.7 cm wavelength, with an automatic tracking capability, was used as the primary
source of position data; the 3.2 and 71.5 cm systems shared an antenna which was slaved,
in azimuth and elevation, to the antenna of the 10.7 cm system thus enabling simultaneous
measurements at the three wavelengths.

Table 1. Characteristics of the Joint Air Force-NASA Radar Facility

Wave-length (cm)	Antenna diameter (m)	Antenna beam-width (deg)	Pulse length (10^{-6} sec)	Antenna gain (db re iso-tropic radia-tor)	Mini-mum detect-able signal (dbm)	Peak trans-mitted power (10^6 watts)	Minimum detectable cross section at 10 km (cm^2)
3.2	10.4	0.21	2.0	58	-101	0.9	1.82×10^{-2}
10.7	18.4	.48	2.0	51	-110	3.0	1.55×10^{-5}
71.5	18.4	2.9	2.0	35	-105	6.0	1.62×10^{-4}

One of the most effective ways to establish the nature of a target is to measure its
radar cross-section or its reflectivity at more than one wavelength.[5] Table 2 illustrates
how the Wallops radars can readily differentiate between backscatter from Rayleigh like
targets and scattering from a refractively turbulent medium. For example, if the pulse
volume of each radar is filled with Rayleigh scatterers, then the signal at 3.2 cm wave-
length will be 3 times greater than that at 10.7 cm and 1000 times greater than at 71.5
cm. On the other hand, if the reflectivity of the scattering volume has a wavelength
dependence of $\lambda^{-1/3}$, as has been reported[5,8,12] for a refractively turbulent medium, then
the signal strength at 10.7 cm will be 28.8 times stronger than that at 3.2-cm and the
signal at 71.5-cm will be 89.1 times stronger than at 3.2-cm. Thus, if the signal is

Table 2. Ratios of Signal Strength from Two Types of Scatterers

Wavelength (cm)	Ratio of 3.2-cm received power above minimum detectable to that at 10.7-cm and 71.5-cm.	
	Rayleigh Scatterers	Refractively turbulent medium with $\lambda^{-1/3}$ wavelength dependence.
3.2	0	0
10.7	3.0	28.8^{-1}
71.5	1000	89.1^{-1}

received at 71.5-cm and no signal is detectable at 3.2-cm at the same range, it is certain that the mechanism giving rise to the radar echoes is not scattering by Rayleigh particles. Expressed differently, if a uniform cloud is detected out to 10 km at 3.2-cm, it will only be detected to 5.8 km at 10.7-cm and to only 0.32 km at 71.5-cm. Similarly, a refractively turbulent medium detected out to 10 km at 3.2-cm would be detected out to a range of 54 km at 10.7-cm and nearly 100 km at 71.5-cm.

THE OBSERVATIONS

Diurnal Characteristics

On September 3-4, 1965, radar observations of the clear atmosphere were made over a continuous 24 hour period.[6] During these observations, a large anticyclone, oriented northeast-southwest, was situated along the northeastern coast of the United States. A cirro-stratus overcast was present until about 2000 EST September 3, and thereafter the period was completely clear. Figure 1 shows a representative time series of Range-Height Indicator (RHI) photographs for the three radars taken along an azimuth of 260°. Starting at 1100 in the upper left of the figure, there are three types of radar echoes. The cirrus cloud displaying several fine-scale streamers is clearly evident at heights of 6-11 km as seen at the two shorter wavelengths. At 71.5-cm there is a weak diffuse layer from 6-7.5 km. This layer corresponds to the height of the lower portion of the cirrus cloud layer. However, from Table 2, it is seen that the signal strength at 3.2-cm would have to be 1000 times stronger than the minimum detectable signal at 71.5-cm before the 71.5-cm radar would detect the particle scatter from the cirrus ice crystals. Signal intensities were not measured in the cirrus cloud at this time, but subsequent observations

indicated that such a large signal strength at 3.2-cm was improbable. It therefore appears likely that the 71.5-cm echoes above 6 km must be caused by refractive index changes which occur within the cloud or at the cloud boundary.

Immediately below the cirrus cloud base at a height of about 4.5-5.5 km there is a well pronounced layer appearing on the 71.5-cm RHI. This layer corresponds to the fine weak layer near 5.5 km as seen at 10.7-cm. No such layer is seen at 3.2-cm, and from Table 2, it can readily be concluded that the layer is not caused by particle scattering but instead is caused by scatter from a refractively turbulent medium. Based on the same type of reasoning, the prominent surface layer seen at 71.5 and 10.5 cm is also caused primarily by turbulent scatter.

The third type of echoes seen at 1100 are the numerous dot targets which are clearly evident at 3.2 and 10.7-cm between 1 and 4 km. In the next sections, we will consider these, as well as all other dot targets, in more detail and will compare their characteristics with those of known birds and insects.

There is often a tendency for the dot targets to congregate in fairly well defined layers.[3,4] The dots which appear at 1100 (also 1335 and 1740) in Figure 1, however, do not show any obvious preference for selected altitudes except that they do not occur above a well defined height near 4 km.

The cirrus cloud slowly dissipated from about 1400 to 2000 September 3, and will not be discussed any further. The clear air layer near 5.5 km which was present at 1100 at both 10.7 and 71.5 cm is just barely visible at 71.5 cm by 1335. The surface clear-air layer is still very strong at 1335 and there is evidence of a wavy structure near the top at 10.7 cm. By 1740 the layer was split in two, one section remaining near 1 km and another section present near the surface. Because of the broad beam width of the 71.5 cm radar (2.9°) the two layers seen at 10.7-cm are effectively merged into one layer at the longer wavelength although the layer is quite blobby. The layer near 1 km corresponds to the base of a very sharp inversion and is clearly the top of the convective mixing zone.[6]

The concentration of dot targets increases slightly from 1100 - 1740. Sunset occurred at about 1830 on September 3. The most notable change between the RHI's at 1740 (~50 minutes before sunset) and those at 1912 (~40 minutes after sunset) is the lowering of the maximum height of the dots from about 3.5 to 2 km. Also it can be seen that at least on a qualitative basis the number of dots near the surface has increased greatly by 1912. The clear air layer at 1 km which was prominent at 1740 has disappeared entirely or is obscured by the dot returns at 1912. The clear air surface layer still exists at 71.5 cm and probably also at 10.7 cm although the return from the dots makes it difficult to distinguish between the two at the shorter wavelength.

The period from 1912 to sunrise at 0530 is marked by a gradual decrease in the number of dot targets. It can be seen that during the night most of the dot targets are very close to the surface. A few, however, continued to be observed at altitudes near 2.5 km.
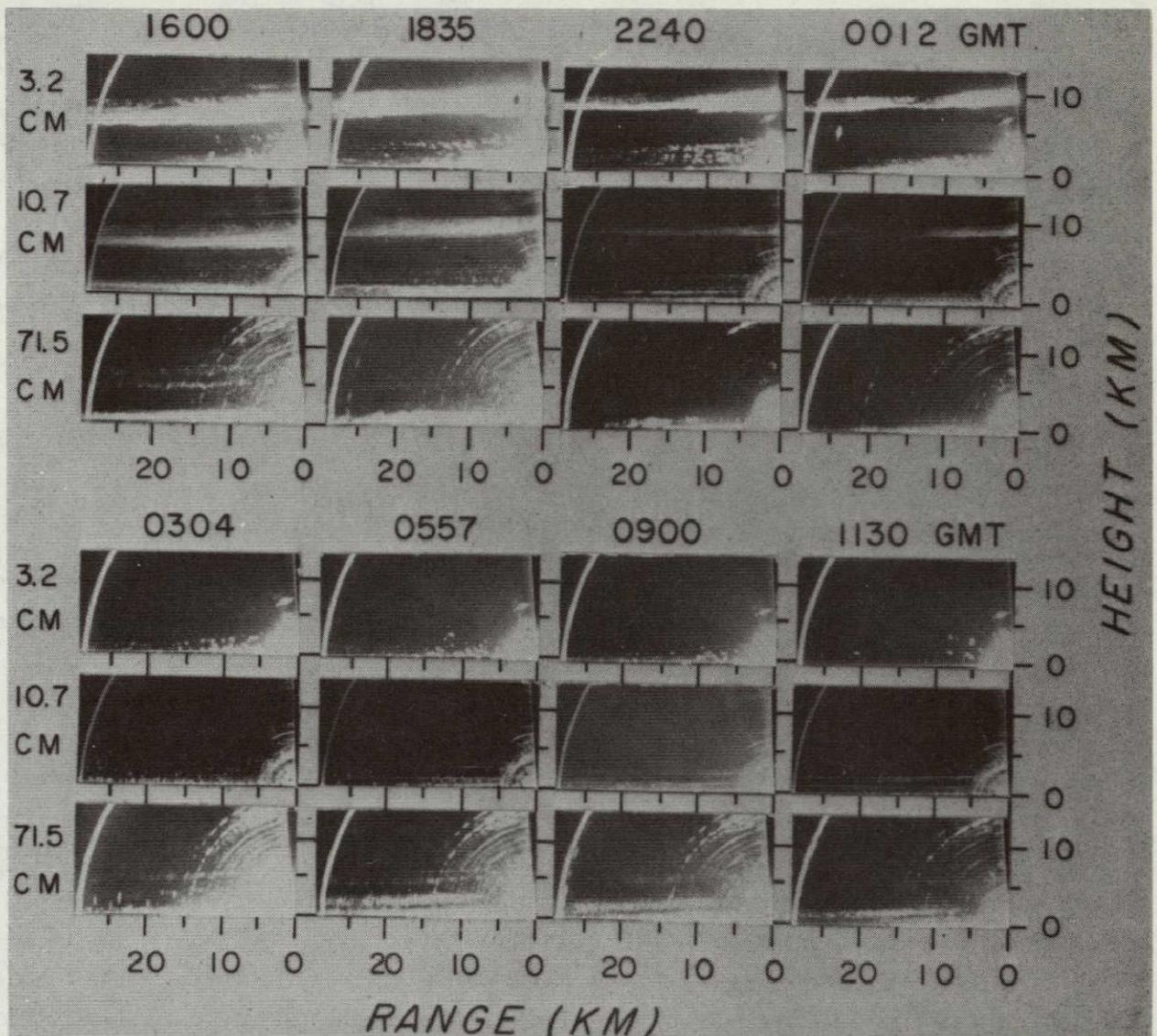
Figure 1. Time series of RHI's at three wavelengths taken along an azimuth of 260°. Because of an error in the scope elevation drive, the baseline of the 3.2 and 71.5 cm RHI's is at an elevation angle of about 2°. This results in the incorrect appearance of downward sloping layers.

By 0630 there are relatively few dot targets near the surface, whereas there are several at the two shorter wavelengths which occur near the 3-4 km level.

Returning to the clear-air layers at 2204, it is seen that in addition to the surface layer which continues to be reasonably strong, the weak layer near 5 km has reappeared at 71.5 cm. By 0057 several layers appear at 71.5 cm; the two lower ones are very strong, whereas two weaker layers occur near 4 and 6 km. At 10.7-cm a strong layer has formed near 1 km and segments of layers occur between 2 and 3 km. At 0400 and 0630 there is a strong layer near 1 km, an equally strong layer near 2 km at the two longer wavelengths, and a weak layer near 5 km at 71.5 cm. At 0400 there is a faint layer echo near 2 km at 3.2-cm. This is one of the few occasions that a true clear-air echo layer was observed at 3.2 cm.

Tracking Characteristics - Dot Targets

During the period September 2-4, 1966, a number of dot targets were briefly tracked in order to obtain a reliable measure of their wavelength dependence, and occasional dot targets were tracked for longer periods in order to measure tracking and radar cross-section fluctuation characteristics of these targets.[8]

Targets were acquired by monitoring a fixed volume in space until the first dot target came into view. Once this target appeared to cross the center of the radar beam, the tracker was switched to the automatic mode and signals proportional to the power received from the target were recorded using an X-Y plotter with time as the abscissa. Azimuth, elevation and range data were sampled simultaneously and recorded once every second with a high speed printer.

Each dot target observed using this method appeared to be a highly trackable target whose characteristics fell into one or two classes. A two-minute segment of an altitude track for a sample from the most common of the two classes is shown at lower left in Figure 2. This target maintained a relatively constant altitude of just under 2.3 km in an ambient temperature of 10°C. Such a constant altitude track was typical of this class, although rises and falls in altitude were observed in many tracks, and an occasional track exhibited a prolonged decrease in altitude with time.

The corresponding ground path of this sample is shown at lower right in Figure 2 for 10-second intervals over the 2 minute period together with a vector corresponding to the average wind encountered by the sample. As was frequently observed, the average path was very nearly a straight line; however, the magnitude and frequency of the erratic oscillations which mark this track were the limits of those generally observed. A comparison of the average dot target and wind velocities showed that this target moved with an average speed relative to the wind (target air speed) of 5.9 m sec^{-1} at an angle of 200 degrees
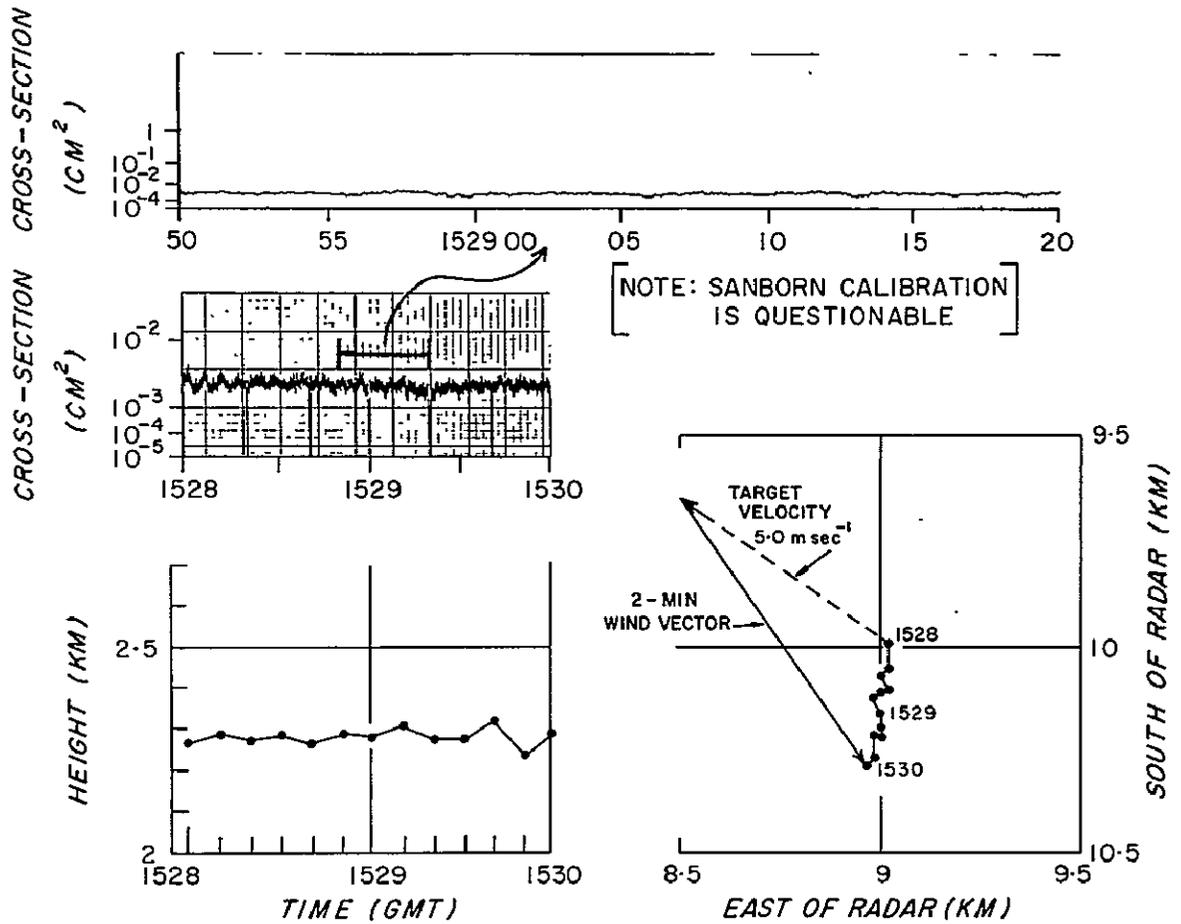
Figure 2.   Typical example of 10.7-cm tracking data for a dot target of the
first class taken on September 2, 1965.

from the wind. Target air speeds for other members of this class fell between 2 and 6 m sec^{-1} and were directed randomly relative to the mean wind.

A continuous 2 minute record of the radar cross-section (σ) of this dot angel, as measured with the 10.7-cm radar, is shown at the left center of Figure 2 and a shorter but expanded section is shown at the top of this figure. Over this 2 minute record, the radar cross-section remained within 1.4 db of the mean at 3.0 x 10^{-3} cm^2. Although similar data for all samples in this class showed 10.7-cm cross-sections which varied between the limits of 5 x 10^{-4} and 5 x 10^{-1} cm^2, it was found that targets observed at a given point in space over a limited time had cross-sections which were constant to within ± 5 db.

Tracking data typical of the second class of dot angels are shown in Figure 3. This sample, like those of Figure 2 was observed to maintain a relatively constant altitude over the sampling interval. In general, however, similar altitude tracks of other "angels" of this class were quite variable; some oscillated about a given height and some descended or ascended for prolonged periods, usually of the order of minutes. Air velocities for this class were much larger than those of the first class. The sample of Figure 3 moved with an average air velocity of 13.6 m sec^{-1} directed at an angle of 196 degrees from the wind. Similar observations made on September 4, 1965, both before and after those of Figure 3, showed average air velocities ranging from 13.6 to 15.9 m sec^{-1} over comparable periods of time. The 10.7-cm cross-sections of this class were large and had large fluctuations. The range of fluctuations shown was typical of the class; however, the manner in which the cross section varied appeared to be different for each track.

Tracking Characteristics - Known Insects

In order to develop a means of distinguishing echoes due to insects from those due to truly atmospheric clear air phenomena, a series of measurements of the radar back-scattering properties of known insects in free flight[7] were conducted at Wallops Island during August and September 1965.

Insect specimens were fed sugar water, placed in individual containers, and then loaded aboard a small single engine aircraft. Once airborne, the aircraft was acquired by the automatic 10.7 cm tracking system and the aircraft was then vectored along a radar radius parallel to the prevailing wind vector. The plane continued an outbound radial course until the altitude and range from the radar were at least 1.5 and 10 kilometers respectively. If the region surrounding the aircraft was then observed to be completely free of all other radar targets, a single insect specimen was ejected into the slip stream of the aircraft. Simultaneously, the automatic tracking of the aircraft was halted with the radar beam fixed upon the drop zone. As the plane continued moving away from the
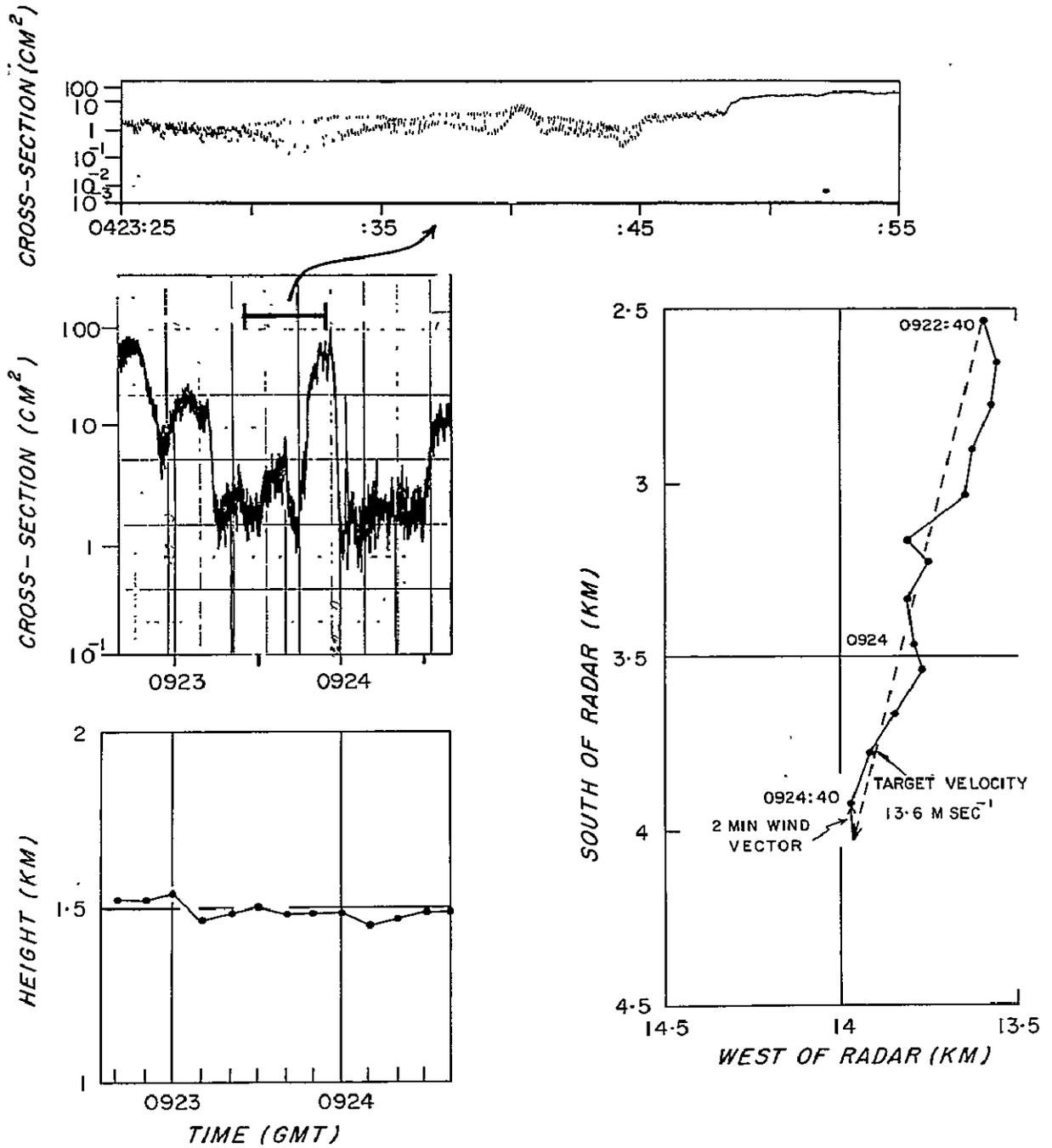
Figure 3. Typical example of 10.7-cm tracking data for a dot target of the
second class taken on September 4, 1965.

radar, it gradually passed out of the primary radar beam leaving just the sample insect in free flight within the drop zone.

This separation of targets appeared on the radar in 9 to 10 seconds after release as a relatively small amplitude insect echo gradually breaking away from the much stronger aircraft echo. Approximately 30 seconds after release, the two echoes were separated sufficiently in range for the automatic tracking circuitry of the 10.7-cm radar to follow only the insect. Once a specimen was acquired in the automatic mode, signals proportional to the power received from the targets were recorded using an X-Y plotter with time as the abscissa. Azimuth, elevation, and range data were sampled simultaneously once every second and recorded on a high speed printer.

In all, four species of insects of differing size and shape were studied at altitudes of 1.6 to 3.0 km and temperatures from 7 to 12°C. Observations were obtained for adult tobacco hornworms or hawkmoths, tobacco budworms, dragonflies, and honey bees. Each species used in these experiments was selected on the basis of its size and general availability. The likelihood of a given species resembling a dot angel was not a determining factor in its selection.

The results[7] for the worker honey bee, are shown in Figure 4. This figure is titled "Probably One Honey Bee" because the acquisition phase of the track took 12 seconds longer than the fairly standard time of 30 seconds observed for the other specimens; however, the "Probable" honey bee was first observed after the same amount of elapsed time (9 sec) as required by the other targets and the same (or what appeared to be the same) target remained in view until acquired in the automatic mode. Thus, there is a fairly high probability that the target tracked was actually a honey bee, but a small possibility does exist that another target could have moved into the beam during the relatively lengthy acquisition period and was subsequently tracked.

The honey bee track is marked by a nearly horizontal path, a large ground velocity relative to the wind (6.7 m sec^{-1} at an angle of 72 degrees to the wind) and a relatively constant cross-section (of mean 3.6 x 10^{-3} cm^2). The constancy of the altitude and the magnitude of the insect velocity establishes the honey bee as a strong flyer capable of maintaining a significant velocity relative to the wind for relatively long periods of time.

There are many similarities between the honey bee track of Figure 4 and the corresponding data for first type of dot target shown in Figure 2. For example, the dot target maintained a mean air velocity of 5.0 m sec^{-1} while flying at a relatively constant altitude of 2.3 km. Moreover, the average 10.7-cm cross-sections of the dot target and the honey bee are nearly identical.

Previous experience has shown that at the radar ranges used in these experiments, errors associated with pointing the narrow radar beams to the same point in space during a track are sufficiently large, even with partial (azimuthal only) electronic parallax
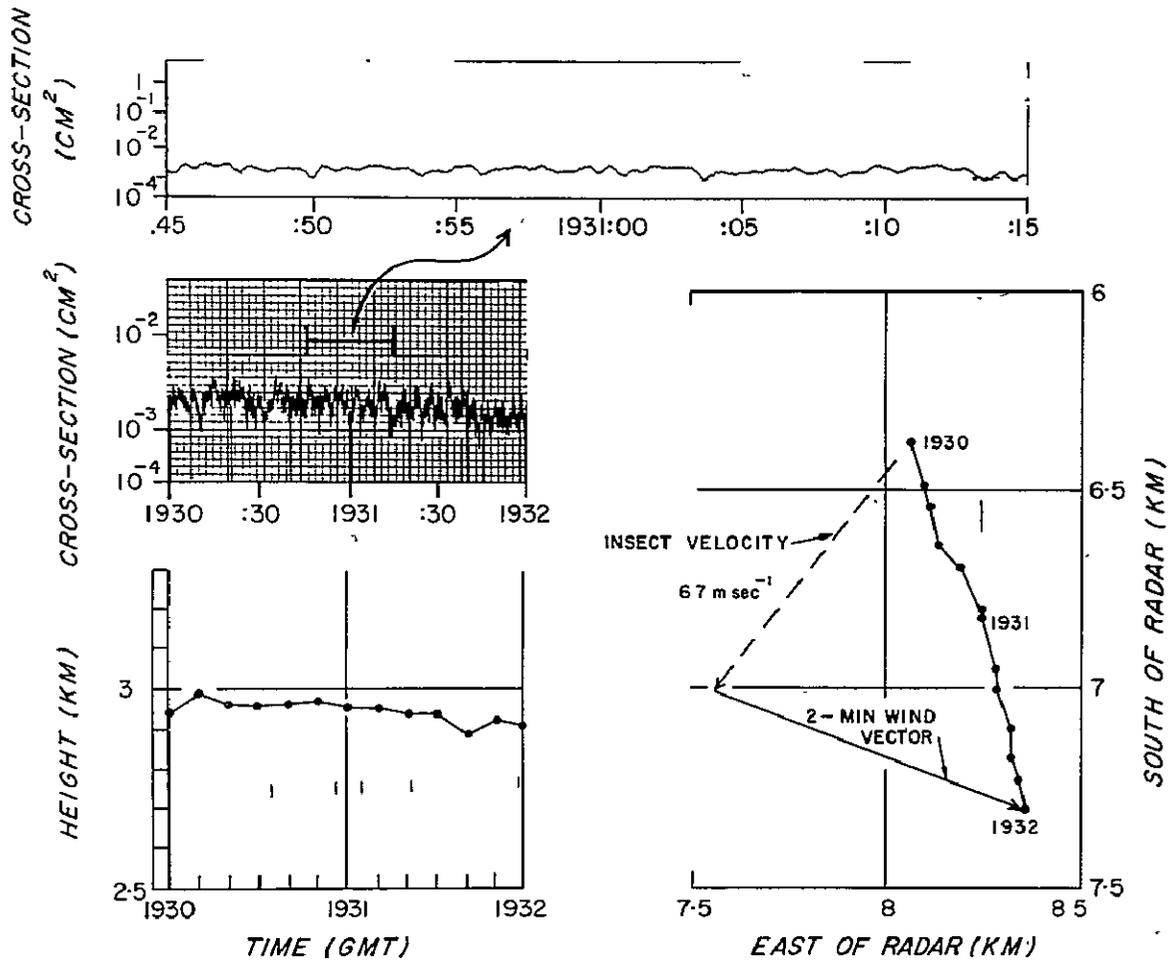
Figure 4. 10.7-cm tracking data of a honey bee (worker) for September 2, 1965.

correction, that representative long time measurements of cross-sections are obtained only with the 10.7-cm automatic tracking radar. In order to insure that the 3.2 and 71.5 cm wavelength beams were boresighted on the same target as the 10.7-cm system for at least part of the time during a track, the 3.2 and 71.5-cm systems antenna was periodically unslaved and slight adjustments in both azimuth and elevation were made to obtain the peak 3.2-cm signal. The maximum cross-sections observed by this means at the three wavelengths for the wingless hawkmoth, the dragonfly, and the honey bee are shown in Figure 5 together with a plot of the radar cross-sections of the first class of dot targets observed on September 3-4, 1965. The cross-section of the worker bee (0.2 cm^2) is in good agreement with 3.2-cm wavelength laboratory measurements of 1.0 and 0.3 cm^2 when the polarization is aligned with the longitudinal and transverse axes respectively.[10] At both 3.2 and 10.7-cm, the absolute cross-sections for the 3 specimens are seen to vary in a complex manner with body length, for the cross-section of the bee is intermediate between those of the hawk-moth and dragonfly and yet both species are much longer than the bee.

Between 3.2 and 10.7-cm, the cross-sections for the above species varied between the limits of $\lambda^{-2.7}$ and $\lambda^{-1.8}$. The 71.5-cm radar system failed to detect even the largest of the specimens and thus, the actual cross-sections of the insects at the longer wavelength fall somewhere below the radar minimum detectable values denoted in Figure 5. The curves between 10.7 and 71.5-cm vary between λ^{-1} and λ^{-3}. Had the signals been detected at 71-cm, the negative slopes would have been greater, conceivably approaching λ^{-4}.

The class one targets tracked on September 3-4, 1965 fall readily into two groups which were observed at different times of day. Daytime targets have 10.7-cm cross-sections in the range of 5×10^{-4} to 2.5×10^{-3} cm^2 and 3.2-cm cross-sections in the range of 1.5×10^{-2} to 2×10^{-1} cm^2. The nighttime targets have cross-sections about 10 db greater at 10.7 cm than the daytime targets, whereas the 3.2-cm cross-sections show little change. Between 3.2 and 10.7-cm, the cross-sections of class one dot angels vary approximately as λ^{-3} for the daytime targets and as λ^{-1} for the nighttime targets. It has been shown[5] that reasonable refractivity surfaces cannot exhibit a wavelength dependence more negative than λ^{-2}. Thus, excluding the possibility of an extremely peculiar refractivity profile, the strong λ^{-2} dependence of the daytime targets virtually eliminates atmospheric structures as the source of these observations. Moreover, the data of Figure 5 clearly demonstrate that insects can account for both the absolute magnitude and the wavelength dependence of the observed daytime angel cross-sections. In view of the mass of supporting data, it must be concluded that the daytime observations of the first class of dot angels are due to insects. The λ^{-1} dependence of the nighttime targets is possibly explainable by a sharp refractivity discontinuity; however, the refractivity gradients required to explain the observed 3.2 cm cross-sections are greater than can reasonably be expected to persist in the atmosphere over periods of tens of minutes corresponding to typical tracking times.[8] Moreover, we should not expect that the sharp atmospheric boundaries required for
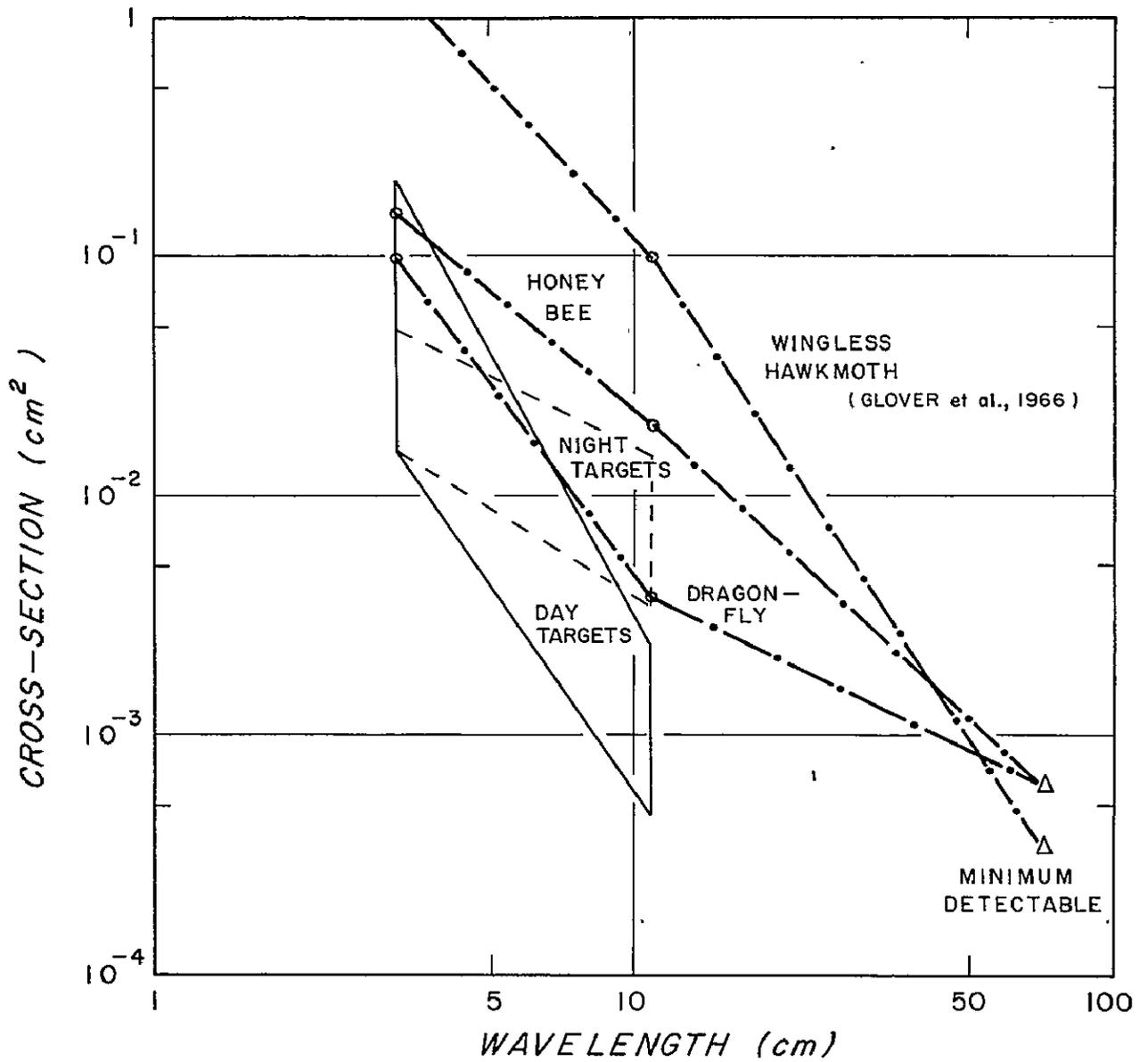
Figure 5. Target cross-section as a function of wavelength for known insects and the first class of dot targets.

this group of targets to be confined to the nighttime. The only remaining possibility is that these nighttime targets are also insects and that the wavelength dependence is a natural consequence of a slight shift of target size of Mie-type scatterers.

Tracking Characteristics - Known Birds

Tracking data comparable to Figures 2, 3, and 4 are shown in Figure 6 for a pigeon in free flight.[9] Despite the fact that the bird obviously didn't care for his environment, there are at least two features of the track worthy of note. First, the great flying ability (21.6 m sec^{-1}) exhibited by this specimen places birds in a position where they can easily account for all of our observations of high dot target velocities. And secondly, the 10.7-cm cross-section record for the pigeon compares quite favorably with the dot target of Figure 3 both in terms of the mean and the extreme values; however, the general character of the fluctuations in the two records is dissimilar.

The radar cross-sections of three species of birds[11] are plotted in Figure 7 as a function of radar wavelength. Figure 7 also includes the limits of the cross-sections of the second type of dot targets observed[8] on September 3-4, 1965. The heavy dashed lines are the mean values for the birds, and the heavy lines are the cross-sections of dot targets of the second class. Vertical arrows at 3.2-cm indicate the range of cross-sections for sparrows and starlings at various aspects from broadside to head-on.[11] The unknown targets have cross-section characteristics which essentially are identical to those for birds. It is interesting to note that the cross-sections of birds at 10.7-cm · are generally larger than those at 3.2 and 71.5-cm. Again this is probably due to the complicated wavelength dependence which is exhibited by Mie-type scatterers. Another feature of the bird cross-sections is the very large fluctuations in cross-section which occur while they are being tracked. Some of this is due to wing beating, but probably the cause of the largest fluctuation is the change in orientation of the bird relative to the electromagnetic radiation. Changes as large as ± 10 db occur over a 2 minute period, although the variations over tens of seconds are usually much smaller (i.e., in the order of ± 3 db). However, the radar characteristics of birds are quite distinctive, and there seems little reason to doubt that they could not be easily recognized, particularly with a multiwavelength radar facility.
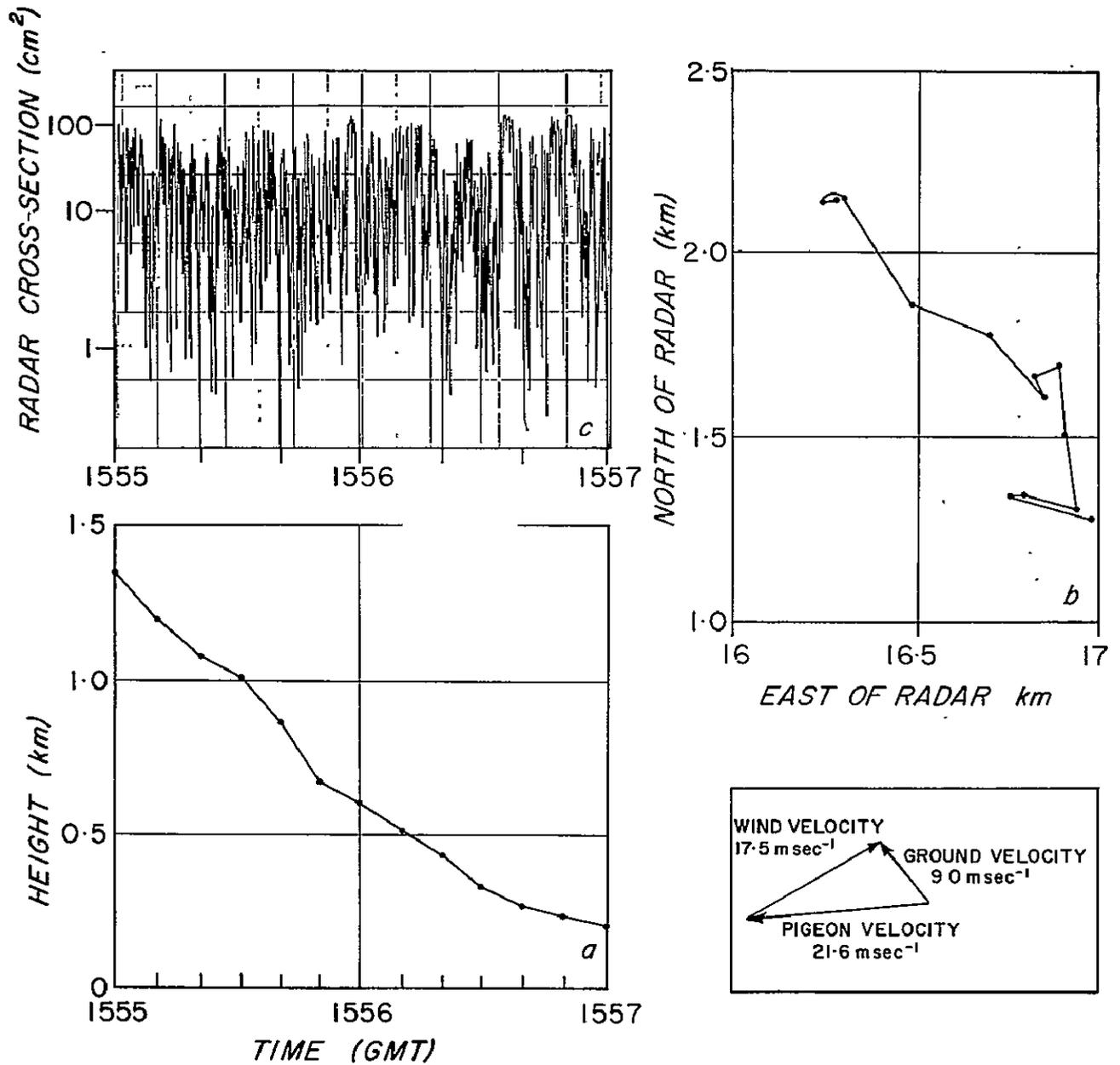
Figure 6.   10.7-cm tracking data of a pigeon obtained on December 8, 1965.[9]
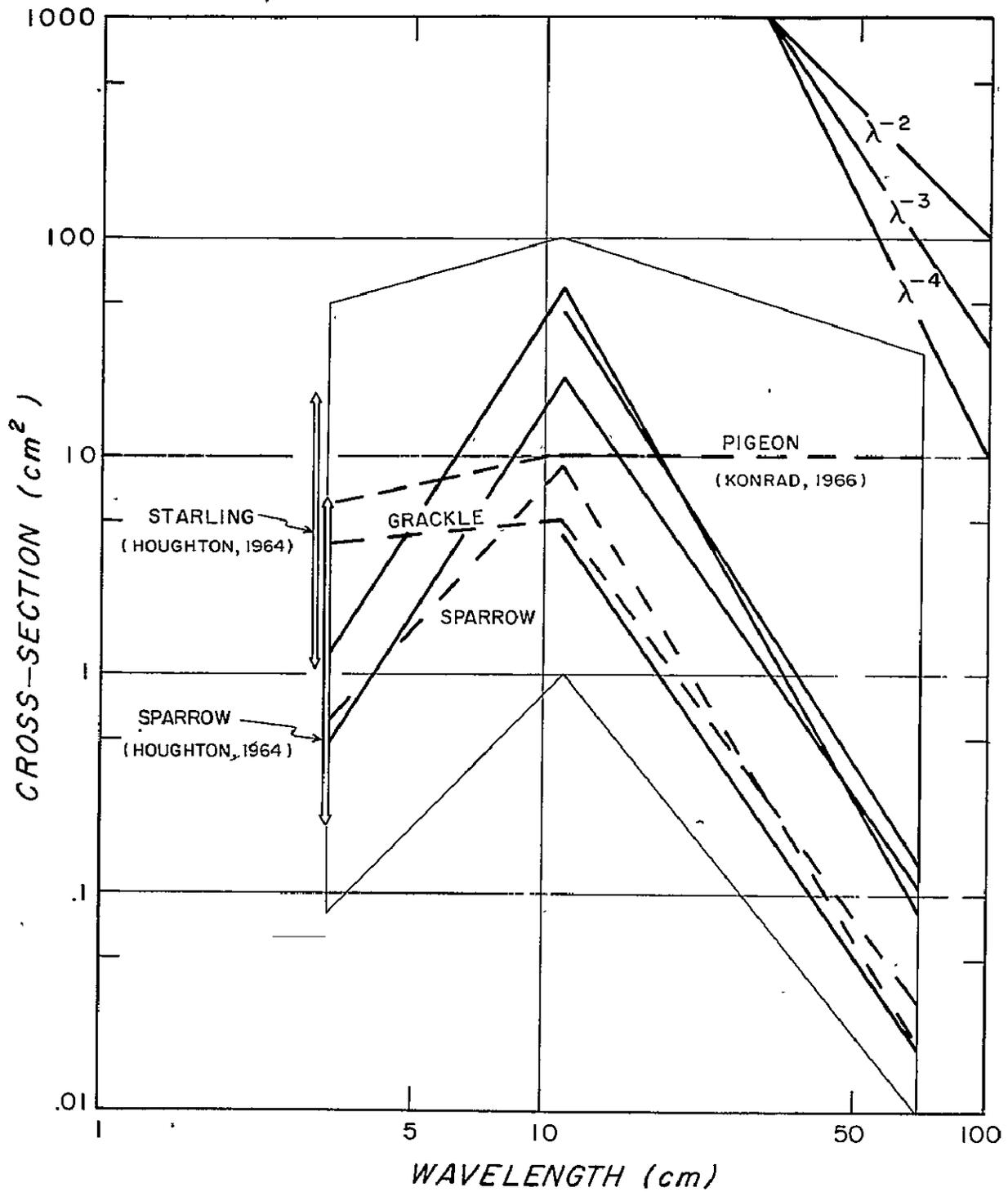
Figure 7.   Target cross-section as a function of wavelength for known birds and the second class of dot targets.

DISCUSSION

The entomological value of these observations lies not so much with particular observations but rather in a demonstration of the potential of radar in investigations of insect free flight behavior patterns and migrations, number concentrations and insect cross-section fluctuation spectral characteristics. In order to identify the various sources of backscatter in the apparently clear atmosphere, sensitive systems such as the multiwavelength Wallops Island radars are required. Sensitivity is required for the detection of refractively perturbed clear-air echoes such as those in Figure 1, and it is a requirement for the detection of insects at relatively long ranges. However, for the majority of potential uses of radar in entomological investigations, far simpler centimeter wavelength radars than those used in these investigations are adequate and may be preferred. The effectiveness of a particular radar in an entomological study can readily be estimated for ranges of interest using the insect radar cross-section data of Figure 5 and the standard radar range equation for a point target.[5]

One final comment is in order with regard to meteorological influences upon insect behavior, especially migratory behavior. As noted in the introduction and documented in radar meteorological literature,[3,4,12] the high correlation in time and space between dot type echoes and meteorological structures leaves little doubt but that these structures affect the migration of insects. Radar can be an effective tool in observing this migrational activity, but forecasting migrational characteristics will require supportive meteorological information necessary to predict the formation, propagation, and decay of the structure(s) which influence the migration of a particular species of insect.

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QUANTITATIVE ANALYSIS OF RADAR RETURNS FROM INSECTS

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INTRODUCTION

Flying insects of mass greater than a few tens of milligrams may be readily detected as individual targets by unsophisticated X-band radars and their flight trajectories conveniently shown on conventional Plan Position Indicator (PPI) displays.[1,2] Maximum detection ranges vary from a few hundred meters to several kilometers for the largest insects.

A good qualitative picture of overall insect movement may be easily obtained by direct observation of the PPI screen. However, quantitative interpretation of PPI displays in terms of aerial density, insect species and trajectory distribution is more difficult, and requires special techniques. This paper describes some of the difficulties encountered in quantitative interpretation and presents methods for dealing with them.

AERIAL DENSITY

In order to interpret the number of "dots" registered on a PPI screen in terms of aerial target density, one needs to know the volume of air sampled by the radar beam as it rotates. Unfortunately the radiation projected by an antenna does not form a sharp edged beam, but decreases gradually in intensity away from the beam axis, and also becomes weaker with increasing range. Thus small targets may be detected at short range and close to the beam axis, while larger targets are detectable at greater ranges and when further from the axis of the beam. The sampled volume thus becomes a function of target "size" or radar cross-section. This effect is illustrated in Figure 1 and a method of calculating swept volume as a function of target size is shown in Appendix I.

The radar cross-section of an insect is usually aspect sensitive[2,3,4] and so, in consequence, the swept volume becomes a function of presented aspect,[5] as well as of insect size. In normal field conditions a variety of insect types may be present at the same time, each type presenting a variety of aspects. It then becomes necessary to
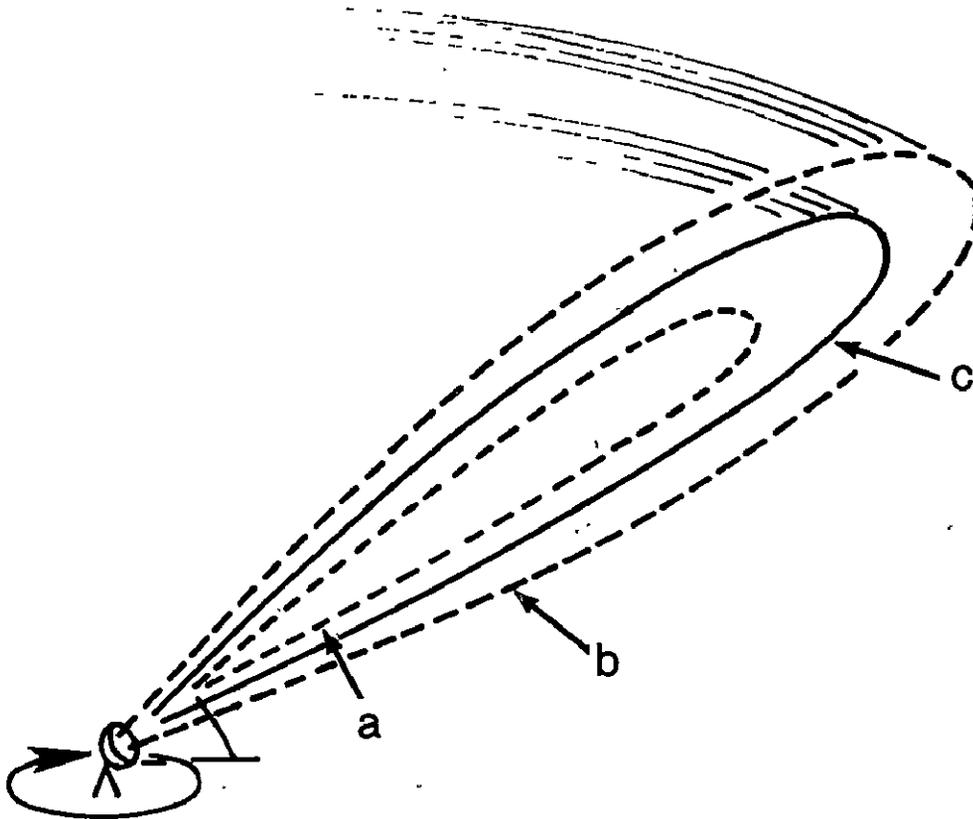
Figure 1. Scanned Volume and Detection Envelopes. The volume swept out for a
particular target size is defined by the appropriate detection envelope
(c). Larger (b) and smaller (a) targets merit correspondingly larger
and smaller envelopes. Note that at the longer ranges, the volume
swept out for smaller targets is zero.

either (a) assume a typical sampled volume, calculated for the average cross-section pre-
sented by the insect targets detectable by the radar at the range of interest, or (b) to
use a procedure of the type shown in Appendix I to establish the actual target cross sec-
tion distribution.

If several insects are present in the radar pulse volume (for our radars typically
10^4 m^3), interference between the targets causes large fluctuations in signal size, and
the targets register irregularly on the screen. Quantitative measurements in these condi-
tions are not usually possible. On the other hand, if the aerial density is sufficient to
ensure that many (>10) targets are present in a pulse volume, volume reflectivity measure-
ments[6] may be used to estimate density, provided that the average cross-section presented
by individual targets is known. The echoes on the PPI screen in these cases are, of
course, of the "solid" distributed type, and individual trajectories are not accessible.

TRAJECTORY DISTORTION AND BIAS EFFECTS

The representation on a flat surface (the PPI screen) of targets detected by a radar, which is scanning with an elevated "pencil" beam, introduces distortion into the displayed trajectories. The distortion, which is a geometrical effect, becomes significant at beam elevations above 25° and affects both direction and displacement speed of the displayed targets. One effect of this distortion is to introduce an artificial spread in the target heading distribution (see Figure II.3).

Several biases also occur which cause some target trajectories to be displayed preferentially. These biases, which are described in detail in Appendix II, have three effects. Firstly, targets on tangential flight paths are more likely to produce measureable trajectories than those on radial paths. Secondly, slowly moving (for example insects flying upwind) targets are favored compared to faster targets and, thirdly, targets flying crosswind are less likely to produce measureable trajectories than up- or down-wind oriented targets.

These biases act simultaneously and combine to make accurate determination of target heading distribution from PPI displays extremely difficult, if not impossible.

CHARACTER OF RADAR RETURNS FROM INSECTS

The signal strength returned to a radar depends on its polarization, and on the target's range, position in the radar beam, and aspect to the radar. In our non-tracking radar system the position of individual targets in the beam is usually unknown and the target aspect uncertain; we have been able to make only limited use of absolute signal levels. For example, in the case of PPI scanning, the maximum range of detection of targets was interpreted in terms of maximum presented cross-section by assuming that at least some of the targets at maximum range were intercepted by the beam axis.

A more useful parameter than this absolute level is the temporal behavior of signal level. Many flying insects produce amplitude modulation of the returned radar signal, the modulation containing components at wingbeat[2,3] and breathing frequencies.[2] Wingbeat frequency provides a useful guide to insect type - small, fast beating insects being readily distinguishable from larger, slower beating types. In many of our field studies, however, a mixture of insects of similar size have been present, and the intra-species spread and inter-species overlap of wingbeat frequency precluded positive identification.[7]

The sensitivity of a target's radar cross-section to radar polarization can also provide clues about target identity.[8,9] Unfortunately, for arbitrary target aspect,

simultaneous measurements of cross polarized return amplitude and relative phase are required and the equipment requirements are complex. We have attempted to avoid this complexity by using a supplementary radar system in which the aspect changes of targets are severely limited. This system projects a circularly symmetric beam vertically upwards in a similar manner to the systems used by Atlas *et al.*[10] and Eastwood,[11] but with the additional feature that the plane of polarization of the beam is continuously rotated (Fig. 2). Targets overflying this radar are thus exposed to controlled changes in polarization, and the consequent variation of returned signal amplitude may be interpreted in terms of body geometry. For example, semi-spherical targets show much less sensitivity to polarization changes than elongated targets.

If the beam is narrow, and provided that the radar cross section, σ, is not a sensitive function of presented aspect at near broadside incidence, then the instantaneous radar cross section will be determined by the target properties and the angle, θ, between the insect body axis and the radar E vector; i.e., $\sigma = f(\theta)$. Insects may be expected to modulate their geometry by wingbeat action and by breathing, so that $\sigma = F(\theta,\psi,\xi)$, where ψ and ξ are the instantaneous phase angles in the wingbeat and breathing cycles. A particular insect type might thus be characterized by a series of identification surfaces in the θ,ψ plane (Fig. 3), or alternatively by a single "surface" in θ,ψ,ξ space. Our measure ments with this system in the field (Fig. 4) suggest that this appears to be the case, but regeneration of the recognition surfaces from radar data has proved difficult to implement. A more readily accessible feature in the data is the target heading which can be deduced (with 180° ambiguity) from the position of the maxima (after correction for beam-shape induced displacement) in the rotation cycle. An example of a "split" heading distribution detected by this technique is shown in Figure 5.

CONCLUSIONS

When the number of flying insects is low enough to permit their resolution as individual radar targets, it is possible to make quantitative estimates of their aerial density using the methods described in this paper. Accurate measurements of heading distribution are not, however, considered practicable using data from a PPI display. The use of a rotating polarization radar resolves this problem and also promises to enhance the wingbeat frequency method of identification.

It is nevertheless emphasized that a great deal of qualitative, but useful, flight information may rapidly be gained from simple scanning radars, and in many situations this is all that will be required for entomological work.

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(a)

(b)
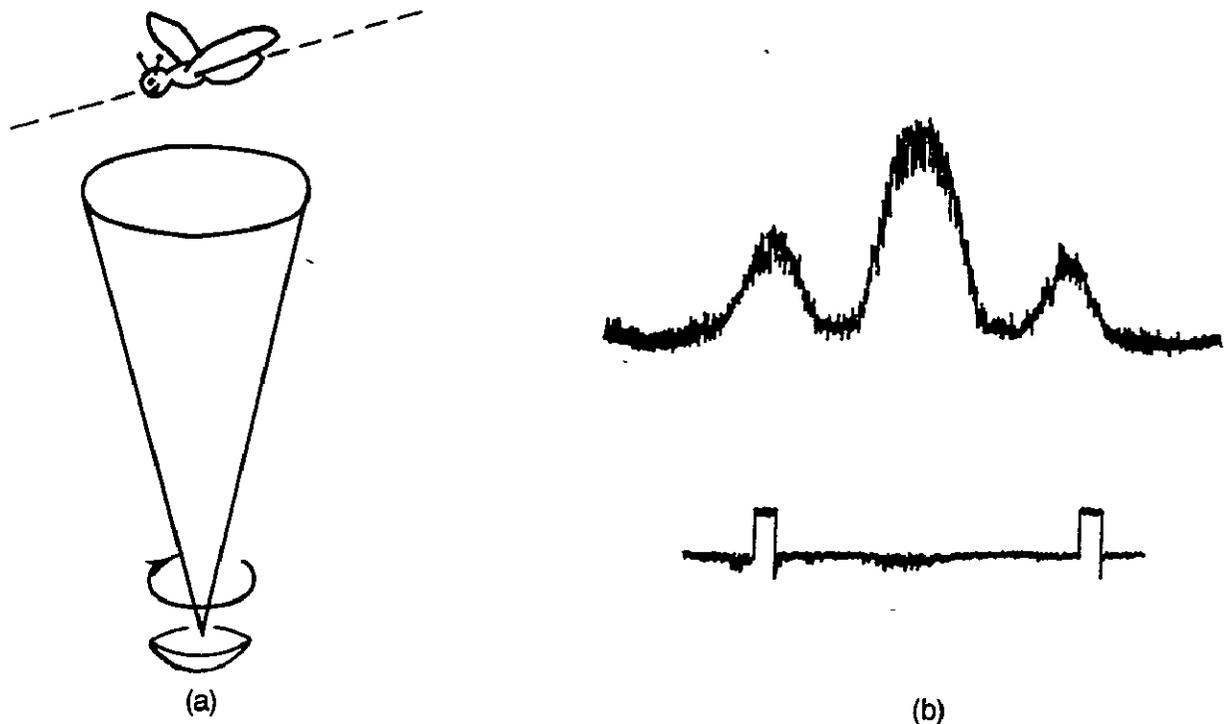
Figure 2. Vertical Looking Radar. (a) Geometry of vertical looking radar. The radar beam is stationary, but its plane of polarization is continuously rotated. (b) Typical returned signal showing wingbeat modulation superimposed on the lower frequency, large amplitude "polarization" modulation. The depth and shape of the "polarization" modulation is determined by the target body shape, long thin targets producing deeper modulation than short fat targets. Maxima normally occur when the plane of (electric) polarization is coincident with the target's longitudinal body axis. The positions of these maxima in the polarization rotation cycle thus accurately fix the target heading (with 180° ambiguity), relative to any selected reference direction. This reference direction is defined by a signal (bottom trace) generated once per feed revolution. The relative amplitude of the three largest maxima determine the beam "transit-time" and hence target displacement rate. Before "body-shape-factor," heading and displacement data can be extracted, the signals have to be corrected for the distortion produced by the (Gaussian) variation of antenna gain with target position.
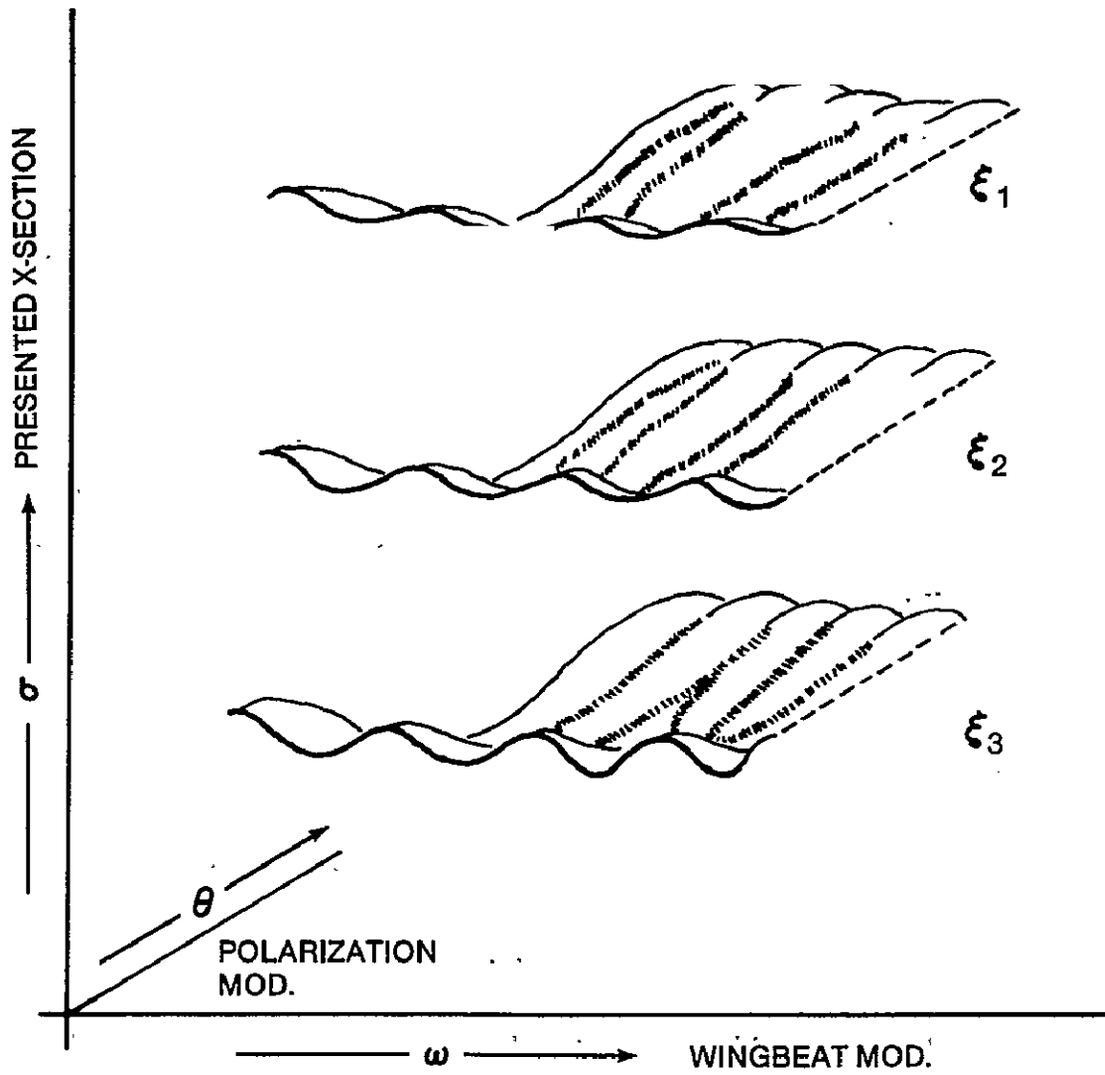
Figure 3. Possible characteristics recognition surfaces generated by exposing flying insects to a rotating polarization radar. ξ represents different breathing phase angles.
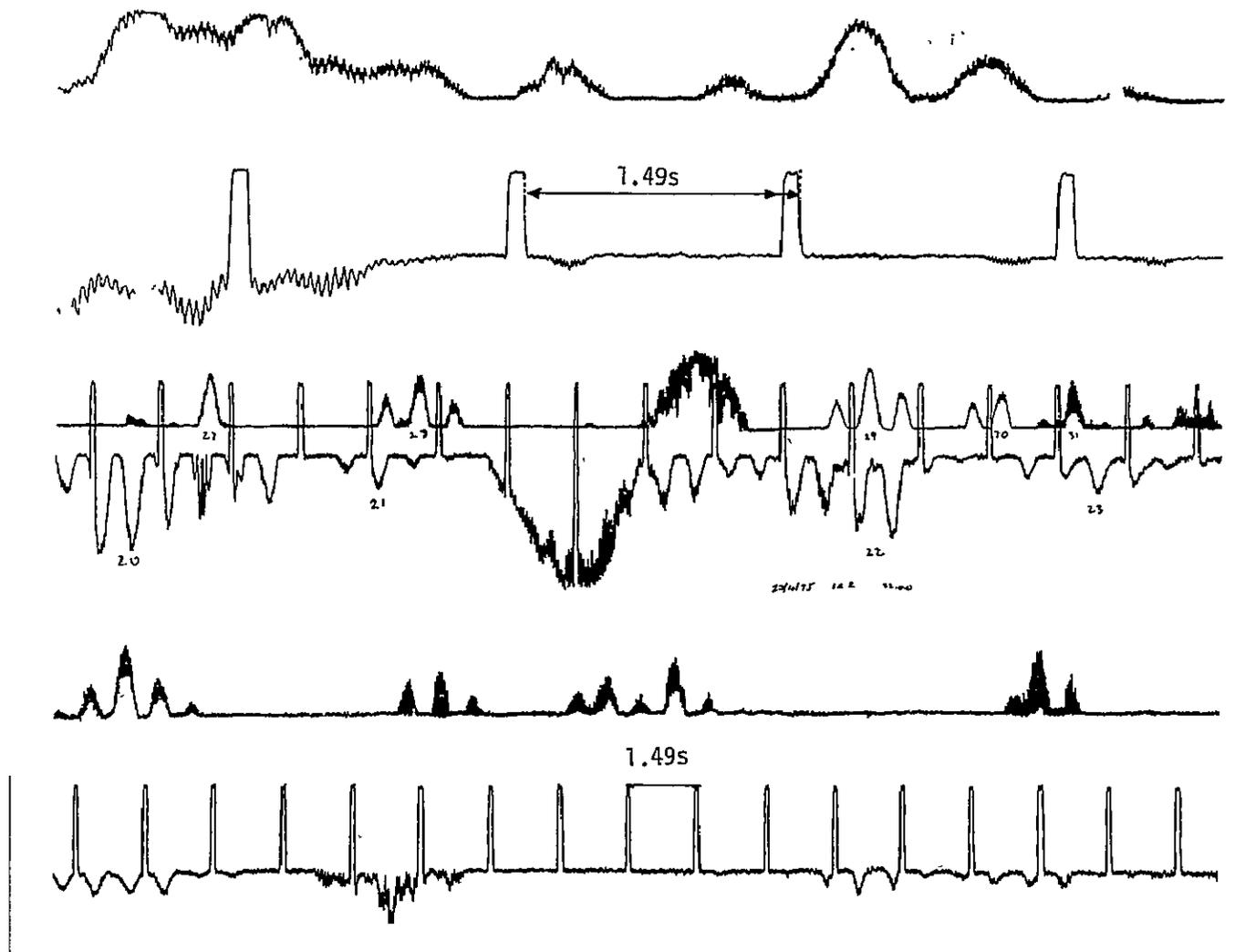
Figure 4. Examples of signals received by rotating polarization radar, shown on different time scales. The repeated rectangular pulse superimposed on one channel is the 'heading marker' signal inserted once per feed revolution.

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10th NOVEMBER 1975   **20·42 — 20·49 HRS.**

300—420m   **420—540m**

540—660m   **660—900m**
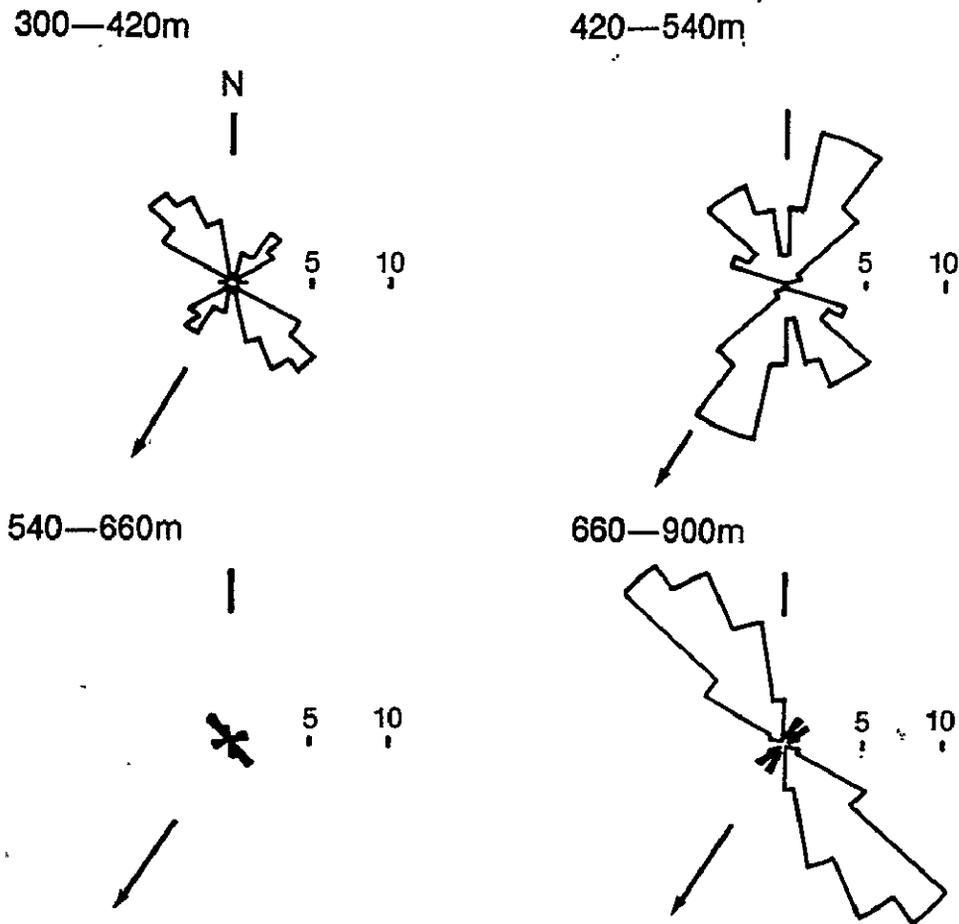
Figure 5. Distribution of insect headings at four altitudes in the range
300-900 m measured by the vertical looking radar at Kara, 20.42 -
20.49 hrs on 10th November 1975. Numbers on the radial scale show
the number of targets in each 6° heading interval. The arrows show
the direction of pilot balloon displacement at the same altitude and
times.

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APPENDIX I

VOLUME SAMPLED BY A RADAR AS A FUNCTION OF TARGET RADAR CROSS-SECTION

A method of calculating the volume sampled by a radar for different target sizes is outlined below, and some typical values for an X-band radar are given.

ISO-ECHOIC CONTOURS OR DETECTION LOBES

The gain of a circular parabolic antenna in an off-axis direction θ, may be described by the expression[12]

$$G_\theta = G_0 \exp\left(-2.776 \frac{\theta^2}{\theta^2_{3dB}}\right)$$

where G_0 is the on-axis gain and θ_{3dB} is the half power width of the beam. The signal power $P_{\theta,r}$ received from an off-axis, isotropically scattering, target is proportional to the square of the antenna gain, and inversely proportional to the fourth power of the target-to-radar range, r.

Thus,
$$P_{\theta,r} = \frac{C}{r^4} \exp\left(-2 \times 2.776 \frac{\theta^2}{\theta^2_{3dB}}\right)$$

where C is a constant determined by the radar properties and target radar cross section, σ_0. The locus of points (or the contour) from which this target will return signals of equal amplitude is determined by setting $P_{\theta,r}$ equal to a constant. Thus, if $P_{\theta,r} = P_{0,r_0}$, where P_{0,r_0} is the power received from the target when on-axis at range r_0, then

$$r = r_0 \exp\left(\frac{-2 \times 2.776}{4} \frac{\theta^2}{\theta^2_{3dB}}\right)$$

Figure I.1 shows an example of the contour derived from this expression for two sizes of antenna.

Targets of different sizes will return signals of the same power from different contours. Thus, for a target of size σ_n, the value of r at $\theta = 0$ is given by $r_{0,n}$, where

-1.5°

(a) 4' dia., (b) 6' dia.;   λ= 3·2 cm

-1·0°

(b)

-0·5°

(a)

0·5

$\frac{r}{r_o}$

1

1·5

0°
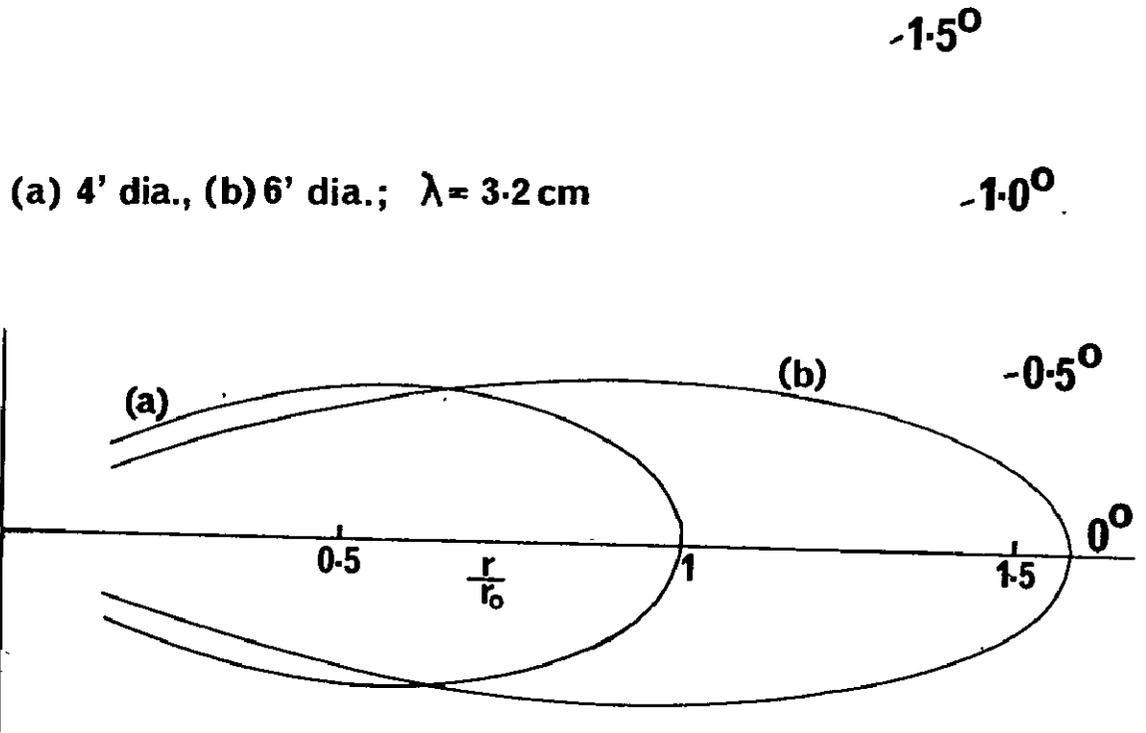
Figure I.1.   Isochoic contours for two parabolic antennas.   Angular scale is
multiplied by 10 to make diagram clear. $\frac{r}{r_o}$ normalized to unity
for on-axis signal of 4' dish.

$$\frac{r_{o,n}}{r_o} = \left(\frac{\sigma_n}{\sigma_o} \right)^{1/4}$$

so that $r_{n,\theta}$, the value of r describing the contour for target of size σ_n, is

$$r_{n,\theta} = \left(\frac{\sigma_n}{\sigma_o} \right)^{1/4} r_o \exp \left(\frac{-2.776}{2} \quad \frac{\theta^2}{\theta_{3dB}^2} \right)$$

Figures I.2 and I.3 show, in different ways, a series of contours for different target
sizes.   The ratio, N, of target sizes is expressed in the diagram in decibels, thus

$$N = 10 \log \frac{\sigma_n}{\sigma_o}$$

6 foot parabaloid

$\frac{r}{r_0} = 1.0$

1·5

0.5

9dB

6dB

3dB

0dB

-3dB

-6dB

-9

θ

4 foot parabaloid

$\frac{r}{r_0} = 1.0$

1·5

0.5

9dB

6dB

3dB

0dB

-3

-6

-9

θ
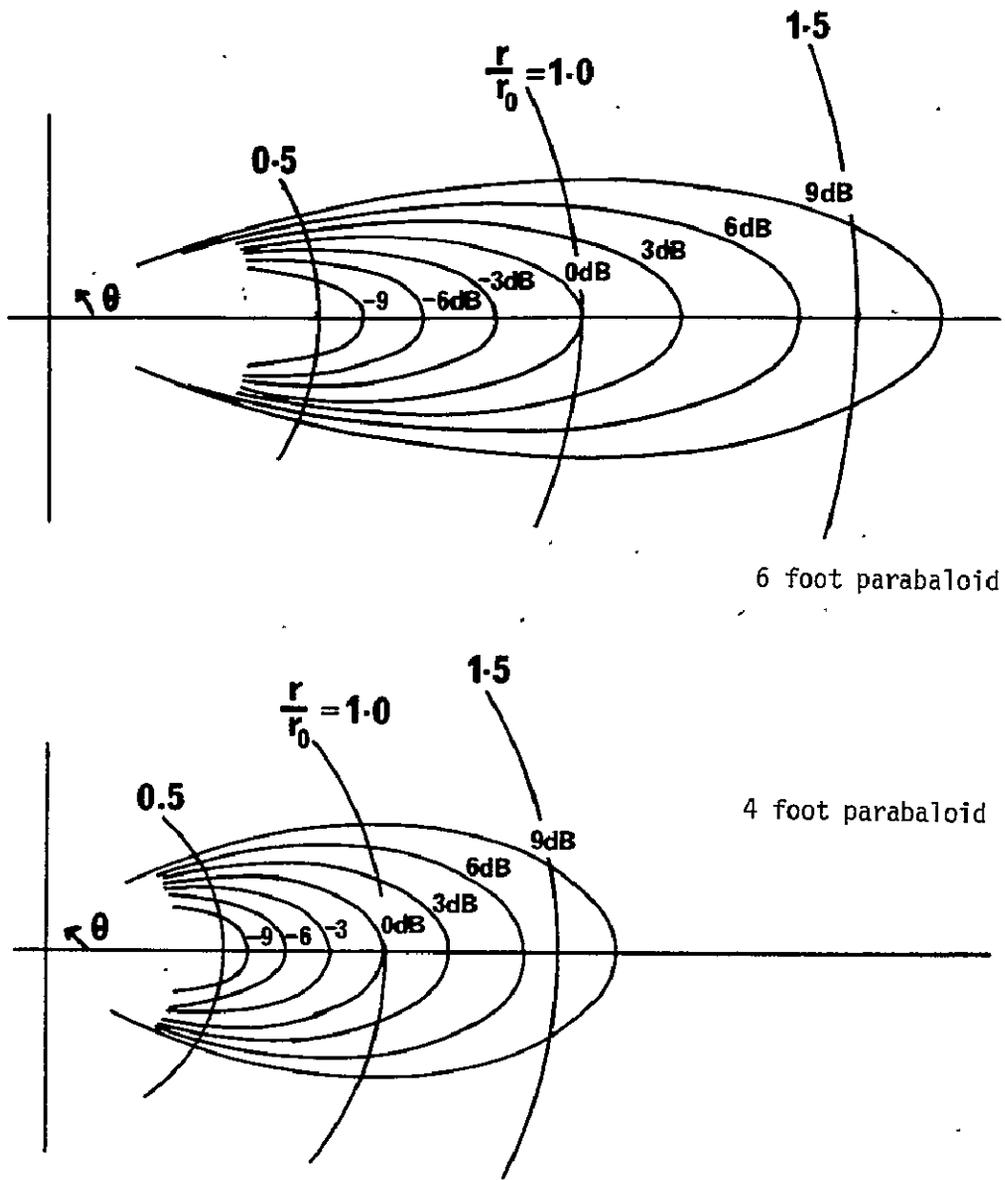
Figure I.2. Detection contours of 6' and 4' parabaloids displayed on same scale. (λ = 3.2 cm). Angular scale multiplied by 10.
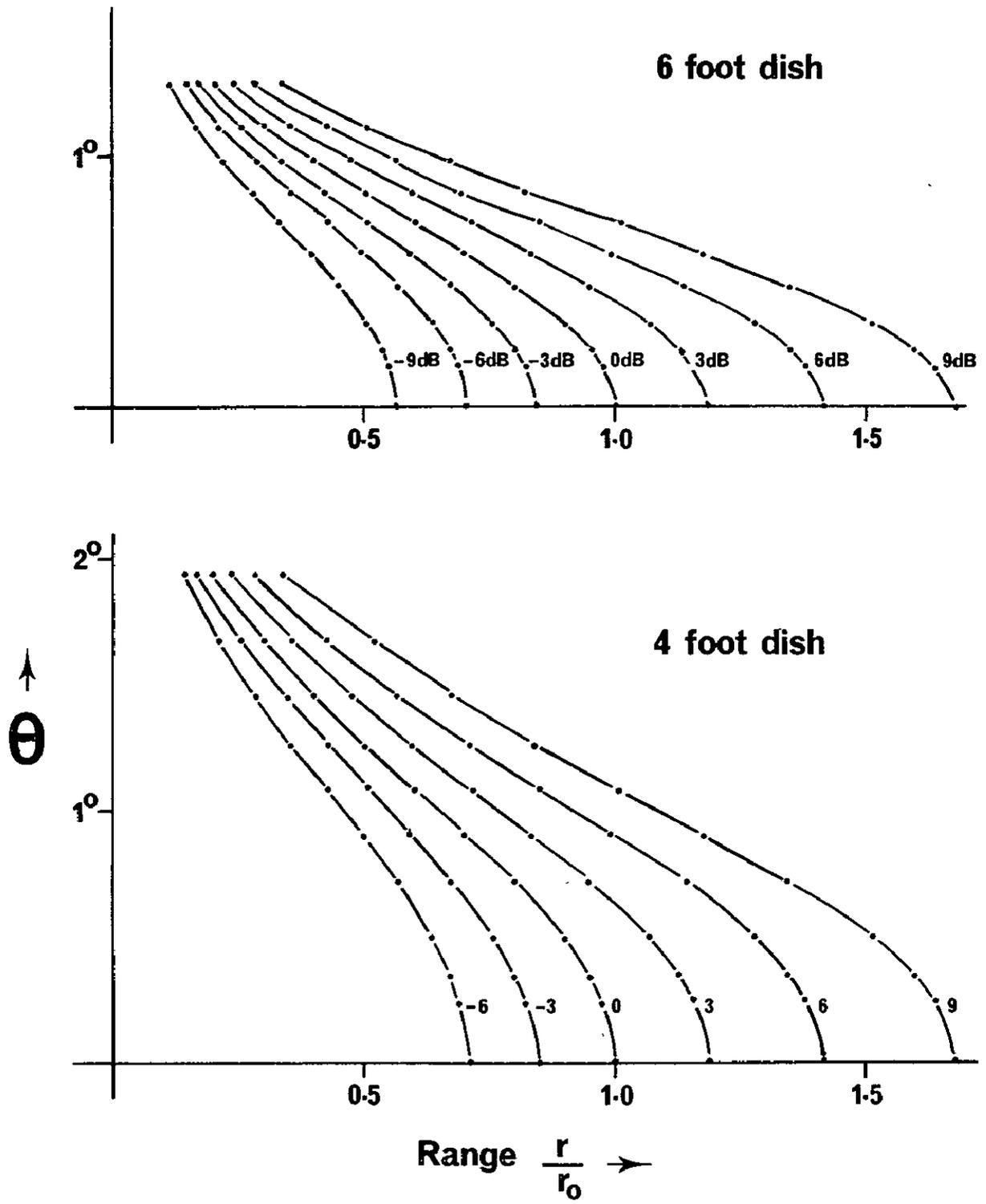
Figure I.3. Detection Envelopes.

If the radar threshold is adjusted to a level corresponding to the signal received from a particular on-axis target, then targets presenting the same radar cross-section will be detected if they occur anywhere within the corresponding contour. The contour will sweep out a volume of space when the antenna is rotated (Fig. I.4) and this is the volume effectively sampled for targets of the selected cross-section.

The detection envelopes are defined by the equation

$$G_0^2 \exp\left(-2 \times 2.776 \frac{\theta^2}{\theta_{3dB}}\right) \frac{1}{r^4} = \text{constant} \tag{i}$$

where the constant has a value appropriate for the radar performance and target size. The volume swept out is

$$V_s = \frac{4}{3} \pi \cos \epsilon \int_0^{\theta_m} r^3 d\theta \tag{ii}$$

where (i) defines the (r,θ) relation and θ_m is determined by the selected minimum range. Equation (ii) is then evaluated with error function integrals.

The volume swept out for a particular target size is defined by the appropriate detection envelope. Larger and smaller targets merit correspondingly larger and smaller envelopes. Note that at the longer ranges, the volume swept out for smaller targets is zero.

large target

small target
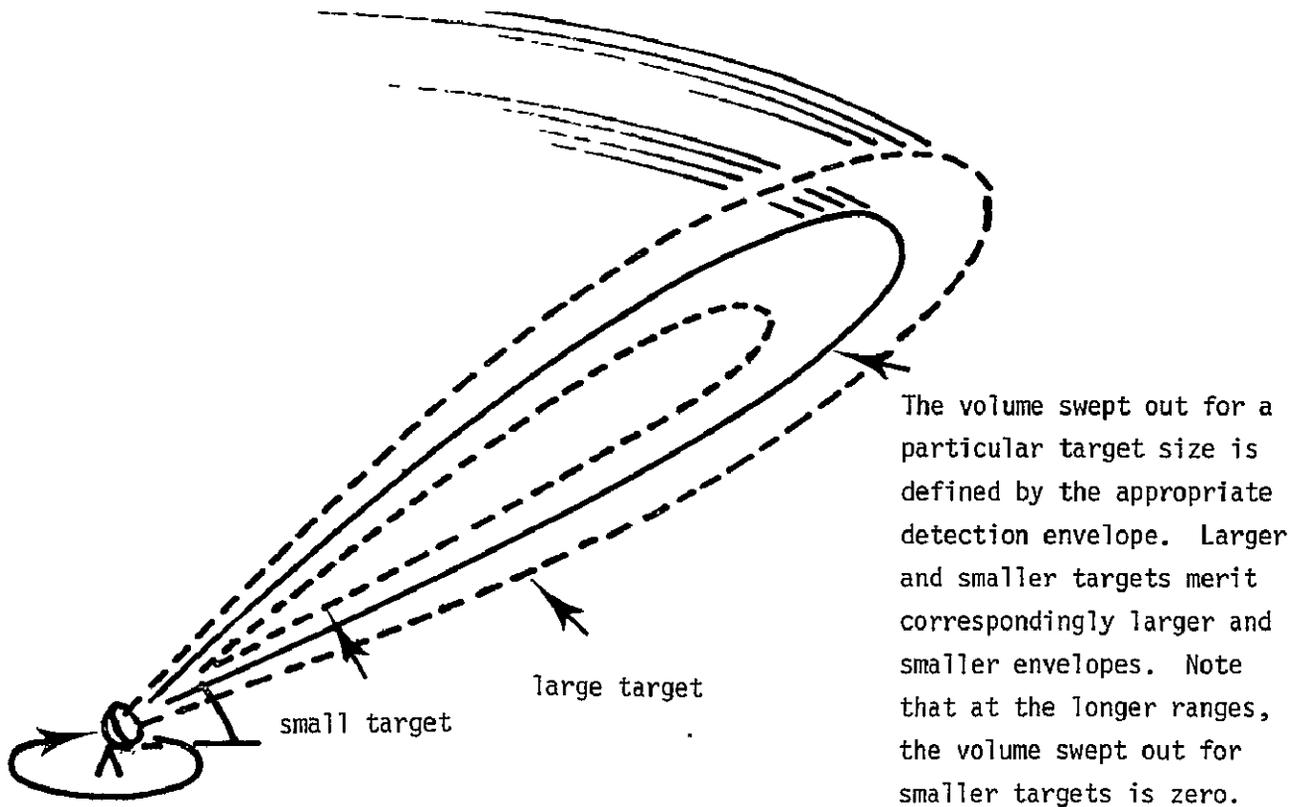
Figure I.4.   Scanned Volume and Detection Envelopes.

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One method of establishing aerial densities is to make a "dot" count in the annulus between two selected ranges r_1 and r_2, and then to calculate the volume swept out between these two ranges by the appropriate contour. Using Figure I.5 as a reference this volume is calculated as follows:
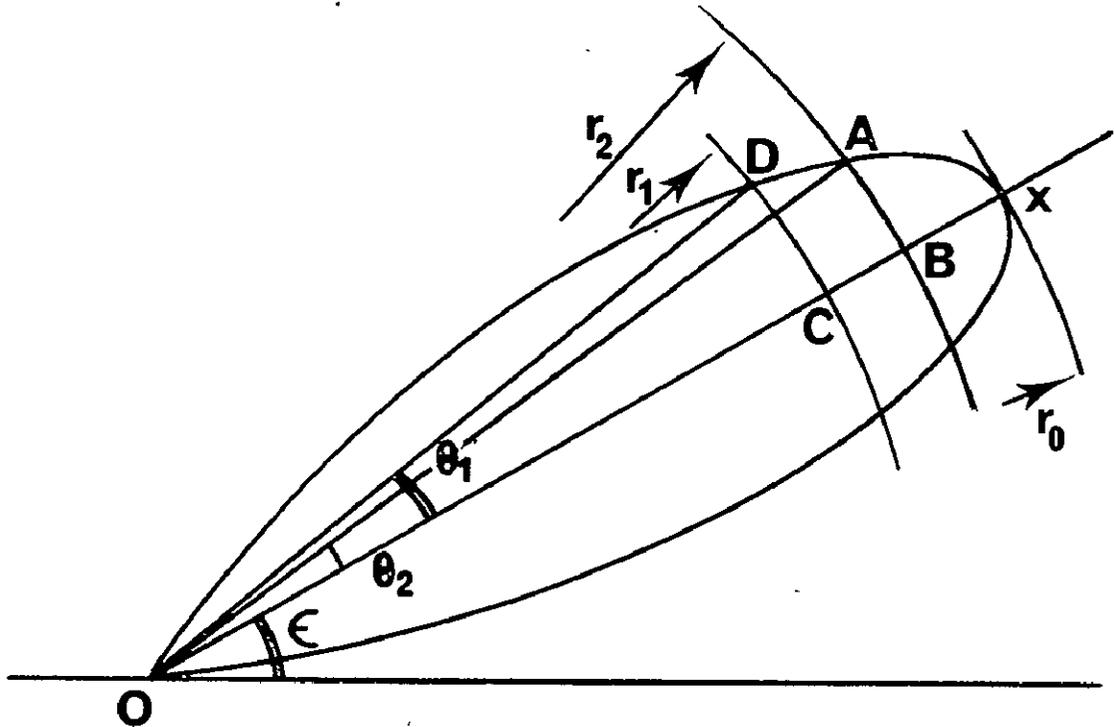
Figure I.5. Volume swept out between two ranges.

The volume swept out by annulus between r_1 and r_2 is

$$V_s = 2 \times (\text{Vol. swept out by DXC} - \text{Vol. swept out by AXB}) \qquad \text{(iii)}$$

But Vol DXC = Vol ODXCO - Vol ODC, $\Big\}$ (iv)

and Vol AXB = Vol OAXBO - Vol OAB .

Now, Vol OAB = $\frac{2}{3} \pi r_2{}^3 \theta_2 \cos \varepsilon$, Vol ODC = $\frac{2}{3} \pi r_1{}^3 \theta_1 \cos \varepsilon$, $\qquad$ (v)

and, using the approximation that $\cos (\varepsilon + \theta) \simeq \cos \varepsilon$ for small θ,

$$\text{Vol ODXCO} = \frac{1}{2} r^2 \ \frac{2\pi \ r}{3} \ \cos \varepsilon \ d\theta = \frac{2}{3} \pi \cos \varepsilon \int_0^{\theta_1} r^3 \ d\theta \qquad \text{(vi)}$$

But for an iso-echoic contour; $r^3 = r_0^3 \exp\left(-2 \times 2.776 \times \frac{3}{4} \frac{\theta^2}{\theta_{3dB}^2}\right)$

Thus, Vol ODXCO $= \frac{2}{3}\pi r_0^3 \cos\varepsilon \int_0^{\theta_1} \exp\left(\frac{-2.776 \times 3}{2} \frac{\theta^2}{\theta_{3dB}^2}\right) d\theta$.

Or, writing $\theta' = c\theta$, where $c^2 = \dfrac{2.776 \times 3}{\theta_{3dB}^2}$

$$\text{Vol ODXCO} = \frac{2\pi}{3} \frac{r_0^3 \cos\varepsilon}{c} \int_0^{c\theta_1} \exp\left(\frac{-\theta'^2}{2}\right) d\theta' . \tag{vii}$$

The same expression applies to OAXBQ, except that $c\theta_2$ is the limit of integration. The integral on the RHS of equation (vii) is the error function integral which may be evaluated from standard tables. So we may write

$$\text{Vol ODXCO} = \frac{2\pi}{3} r_0^3 \frac{\cos\varepsilon}{c} x.$$

But $r_0 = r_2 \times 10^{\frac{N}{40}}$, where N is the number of dB's by which the level of the iso-echoic contour being used exceeds that of the contour passing through point B.

Thus, $\qquad \text{ODXCO} = \frac{2\pi}{3} r_2^3 \frac{\cos\varepsilon}{c} 10^{\frac{3N}{40}} I_2 . \tag{viii}$

Hence from (iii), (iv), (v), and (viii)

$$V_s = \left[\frac{10^{\frac{3N}{40}}}{c}(I_1 - I_2) + (\theta_2 - \alpha^3\theta_1)\right] \frac{4}{3}\pi r_2^3 \cos\varepsilon$$

where $\alpha = \dfrac{r_1}{r_2}$; θ_1 and θ_2 are read from Fig. I.3 at $\dfrac{r}{r_0} = \alpha$ and 1; and I_1 and I_2 are obtained from error function tables.

But the volume swept out by a cone of semi-angle equal to the antenna "3dB" angle is

$$V_{3dB} = \frac{2}{3}\pi r_2^3 \theta_{3dB} (1 - \alpha^3) \cos\varepsilon$$

Thus,

$$\beta = \frac{V_s}{V_{3dB}} = \frac{\left[\dfrac{10^{\frac{3N}{40}}}{c}(I_1 - I_2) + (\theta_2 - \alpha^3\theta_1)\right] \times 2}{\theta_{3dB}(1 - \alpha^3)}$$

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Figure I.6 shows the results of evaluating this equation, and allows one to read off the swept volume in terms of target size relative to a known target. An example of this is shown below.

1. From calibration flight experiments, note r_c the maximum range for PPI detection of the calibration target of known size, σ_c, (at the usual gain and attenuation settings).

2. Then use these two figures to calculate the minimum target size (σ_m) detectable on axis at r_2, the outer band of the measuring annulus. Thus

$$\sigma_m = \sigma_c \left(\frac{r_2}{r_c} \right)^4$$

3. Next calculate the ratio of σ_m to the expected target cross-section σ_t

$$N = 10 \log \left(\frac{\sigma_t}{\sigma_m} \right) \, dB$$
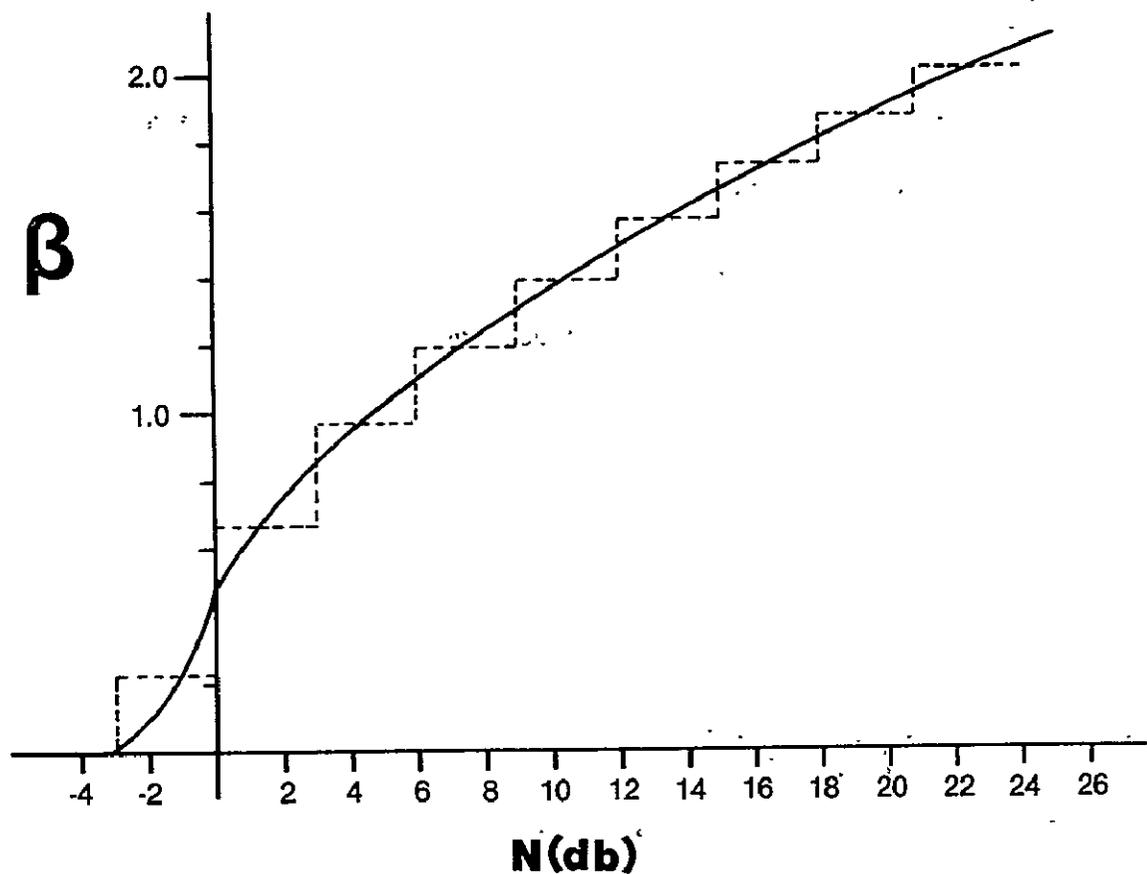
Figure I.6. Ratio of sweeping volume between r_2 and αr_2 to 3db volume as a function of target size, for a parabolic antenna, with r_2 = 1200 yd, and r_1 = 1000 yd, i.e., α = 0.83.

4.   Use N, together with a graph relating N to the ratio β of swept volume to 3dB volume for the antenna (Fig. I.6) to obtain β.

5.   From β and the value of the 3dB volume, calculate the swept volume;

$$\text{Volume} = V_{3dB} \times \beta$$

Example (1) (Type A Radar) $\lambda = 3.2$ cm^2

(i)   For Cu plated ping-pong ball calibration target, $d = 3.78$ cm and $\sigma_c = 16$ cm^2, and $r_c = 2930$ m, $r_2 = 1096$ m (1200 yd), $r_1 \approx 914$ m (1000 yd) and expected target size is 0.5 cm^2.

(ii) $\sigma_m = 16 \left\{ \dfrac{1096}{2930} \right\}^4 = 0.31$ cm^2

(iii) $N = 10 \log \left\{ \dfrac{0.50}{0.31} \right\} = 2.1$ dB

(iv)   From Fig. I.6 for a paraboloid, when $\dfrac{r_1}{r_2} = \dfrac{1000}{2000} = 0.83$; obtain, for $N = 2.1$ dB, $\beta = 0.68$

(v)   For a 6' paraboloid, $\theta_{3dB} = 1.2°$ so 3dB volume between 1096 m and 914 m is

$$V_{3dB} = \frac{2}{3} \pi^2 \times \frac{1.2}{180} \; (1096^3 - 914^3) \cos \epsilon = 2.4 \times 10^7 \cos \epsilon \quad [\text{m}^3]$$

(expressing θ_{3dB} in radians).

Thus, the volume swept for 0.5 cm^2 targets between 914 m and 1096 m is

$$V_s = 2.4 \times 0.68 \times 10^7 \cos \epsilon \quad [\text{m}^3]$$
$$= 1.6 \times 10^7 \cos \cdot \epsilon \quad [\text{m}^3]$$

Example (2) (Type B Radar) $\lambda = 3.2$ cm^2

(i) $r_c = 5030$ m

(ii) $\sigma_m = 16 \left\{ \dfrac{1096}{5030} \right\}^4 = 3.6 \times 10^{-2}$ cm^2

(iii) $N = 10 \log \left\{ \dfrac{0.50}{3.6 \times 10^{-2}} \right\} = 11.4$ dB

(iv)   From graph; for $N = 11.4$ dB, $\beta = 1.42$

Thus, (v) $V_s = 2.4 \times 10^7 \times 1.42$

$$= 3.4 \times 10^7 \cos \epsilon \quad [\text{m}^3]$$

It should be pointed out that the registration of a target above a selected threshold is a statistical process, and depends on the temporal behavior of the target cross-section, as well as the required false alarm and detection probabilities.[12] The contours shown in Figure I.1 thus represent diffuse boundaries between the size categories, rather than precise limits.

MEASUREMENT OF TARGET SIZE DISTRIBUTION

Normally a range of different target cross-sections may be present, and it is necessary to establish the distribution of these cross-sections in order to produce accurate measurements of target density. The problem may be illustrated by pointing out that the volume calculated above for targets presenting cross-sections of 0.5 cm^2 is also sensitive in different proportions to larger and smaller targets.

A method of measuring size distribution is shown below.

Objective

To determine the number of aerial targets per unit volume in each 3dB size interval, starting at 10 cm^2 down to 0.1 cm^2.

(i) From calibration flight results note r_c, the maximum range for a target of size σ_c (typically 16 cm^2).

(ii) Calculate the minimum cross-section σ_m detectable at r_2, the outer edge of the ---uring annulus.

$$\sigma_m = \sigma_c \left\{ \frac{r_2}{r_c} \right\}^4$$

(iii) Calculate the ratio N, where

$$N = 10 \log \left\{ \frac{10}{\sigma_m} \right\} dB$$

To obtain the amount (N) by which the radar threshold must be increased so that targets presenting cross-sections of 10 cm^2 will just be detected on axis at r_2.

(iv) Increase the radar threshold by this amount. The radar is now scanning an average volume $\simeq V_{3dB}$ x 0.2 for targets in the range 10 - 5 cm^2 (See Fig. I.6).

(v) Decrease the IF attenuation by 3dB. The radar is now scanning a volume of 0.68 x V_{3dB} for 10-5 cm^2 targets, plus a volume of 0.2 x V_{3dB} for 5-2.5 cm^2 targets.

(vi). Decrease the IF attenuation by a further 3dB. The radar is now scanning a volume of 0.98 x V_{3dB} for 10 - 5 cm^2 targets, 0.68 x V_{3dB} for 5 - 2.5 cm^2 targets plus 0.2 x V_{3dB} for 2.5 - 1.25 cm^2 targets.

Repeat until 21 dB of IF attenuation has been removed (or normal operating level is reached). Then, if N_1 is the number of targets registered with the first setting,

$$N_1 = n_1 \times 0.2 \times V_{3dB}$$

where n_1 is the aerial density of targets in the range 10-5 cm^2.

If N_2 is the number of targets registered after the decrease of IF attenuation by 3dB

$$\frac{N_2}{V_{3dB}} = n_1 \times 0.68 + n_2 \times 0.2$$

where n_2 is the aerial density of targets in the range 5 - 2.5 cm^2.

Similarly,

$$\frac{N_3}{V_{3dB}} = n_1 \times 0.98 + n_2 \times 0.68 + n_3 \times 0.2$$

$$\frac{N_4}{V_{3dB}} = n_1 \times 1.20 + n_2 \times 0.98 + n_3 \times 0.68 + n_4 \times 0.2$$

$$\frac{N_5}{V_{3dB}} = n_1 \times 1.40 + n_2 \times 1.20 + n_3 \times 0.98 + n_4 \times 0.68 + n_5 \times 0.2$$

$$\frac{N_6}{V_{3dB}} = n_1 \times 1.58 + n_2 \times 1.40 + n_3 \times 1.20 + n_4 \times 0.98 + n_5 \times 0.68 + n_6 \times 0.2$$

$$\frac{N_7}{V_{3dB}} = n_1 \times 1.75 + n_2 \times 1.58 + n_3 \times 1.40 + n_4 \times 1.20 + n_5 \times 0.98 + n_6 \times 0.68 + n_7 \times 0.2$$

The aerial densities of the different groups (n_n) may then be extracted from these equations by sequential solution.

An alternative method is to determine the amplitude distribution of the signals received by the radar whilst scanning, and to use a similar procedure to that outlined above. This method requires, however, a knowledge of the radar IF amplifier and video detector responses.

DISTORTION AND BIAS EFFECTS IN PPI SCANNING

The trajectories of targets which subtend finite angles of elevation from a radar become distorted when displayed on a PPI screen. The distortion, which affects both velocity and target direction, becomes serious above elevation angles of 30°

On the PPI (see Fig. II.1) the apparent velocity, V_a, is

$$V_a^2 = \left(\frac{dr}{dt}\right)^2 + \left(\frac{rd\theta}{dt}\right)^2 \tag{i}$$

But for horizontal straight flight the true velocity, V_t, is

$$V_t = \frac{d}{dt} (a \tan \theta)$$

$$= a \sec^2 \theta \frac{d\theta}{dt}$$

$$= r \cos \varepsilon \sec \theta \frac{d\theta}{dt}$$

so

$$\frac{d\theta}{dt} = \frac{V_t \cos \theta \sec \varepsilon}{r} \tag{ii}$$

And from geometry $r^2 = h^2 + a^2 \sec^2 \theta$; so,

$$\frac{dr}{dt} = r \tan \theta \cos^2 \varepsilon \frac{d\theta}{dt} \tag{iii}$$

Thus, from (ii) and (iii)

$$\frac{dr}{dt} = V_t \cos \varepsilon \sin \theta \tag{iv}$$

(iv) and (ii) in (i) give

$$\frac{V_a}{V_t} = \left\{\cos^2\varepsilon \sin^2\theta + \cos^2\theta \sec^2\varepsilon\right\}^{1/2} \tag{v}$$
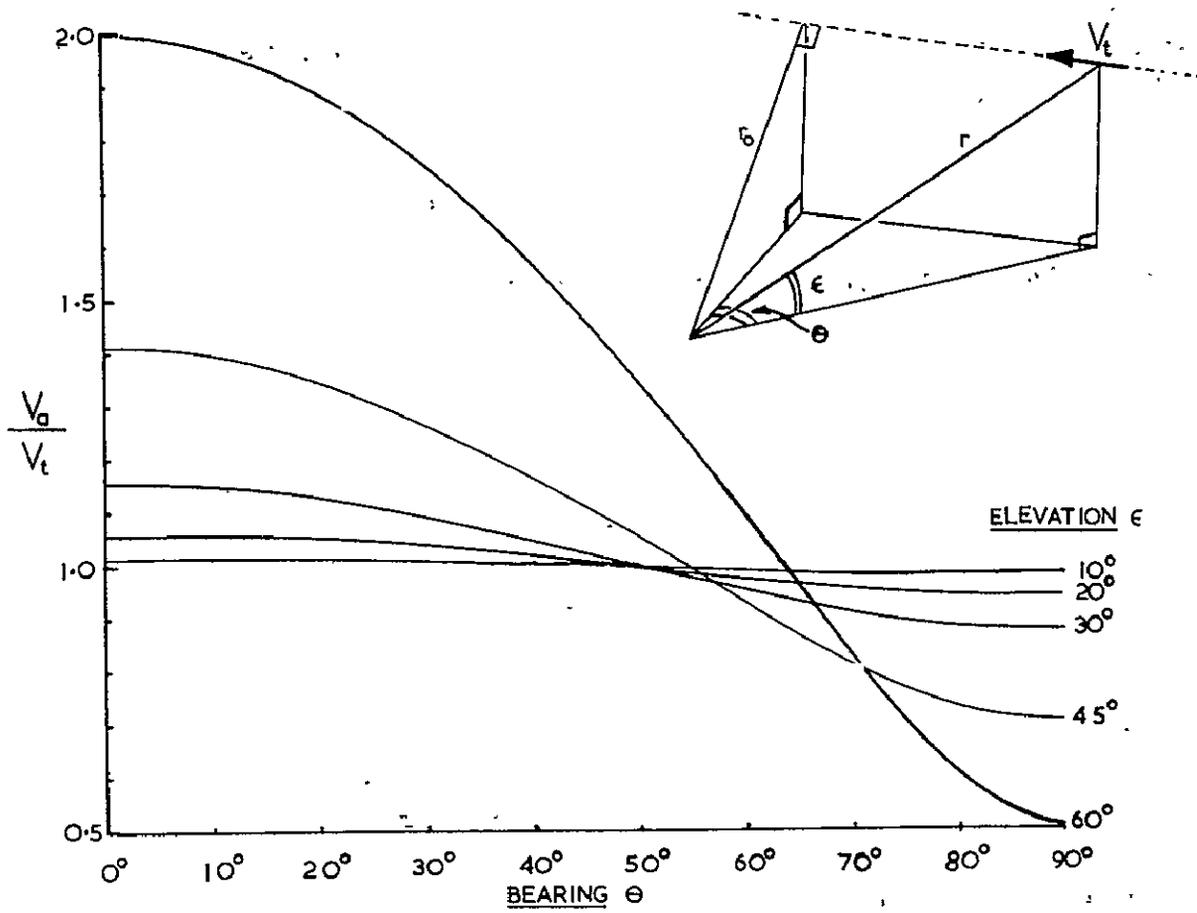
Figure II.1.   The apparent velocity V_a on a PPI display of a target moving in a hori-
zontal straight line with velocity, V_t, varies with target position and
elevation.   The graph illustrates this variation for a selected series
of elevations.   The bearing angle, θ, is measured between projections
onto a horizontal plane of the target position vector, r, and r_0, the
vector defining the distance of closest approach.

The apparent direction of the trajectory as displayed on the PPI is

$$\alpha = \tan^{-1} \left\{ \frac{rd\theta}{dt} \middle/ \frac{dr}{dt} \right\}$$

$$= \tan^{-1} \left\{ \frac{V_t \cos \theta \sec \varepsilon}{\tan \theta \cos^2 \varepsilon \; V_t \cos \theta \sec \varepsilon} \right\}$$

$$= \tan^{-1} (\cot \theta \sec^2 \varepsilon)$$

And' the variation, Δ, from the true direction is

$$\Delta = \alpha + \theta - 90°$$

Values of Δ and V_a/V_t are shown in Figures II.1 and II.2. The overall effect of both distortions is to increase the spread in heading distributions. Fig. II.3 gives examples of the displayed trajectories which would be produced by a group of targets all flying in exactly parallel lines.

As well as this distortion, PPI trajectories are subject to several biases, some target trajectories being displayed preferentially. The first bias varies with the azimuthal position occupied by the target when it is intercepted by the radar beam. The effect is most conveniently demonstrated by calculating the signal variation expected from isotropically scattering targets passing through the scanned volume from different positions.

Referring to Figure II.4, consider the signal returned by a target as it passes from +x through the position r_0, θ_0, ε_0 to -x. At r_0, θ_0, ε_0 the target is intercepted by the axis of the illuminating beam as it sweeps in azimuth, but at other positions along the +x to -x axis, the target is either above or below the beam axis, and the returned signal is consequently weaker. The maximum returned signal strength can be computed by calculating the angle subtended between the radar-target line and the beam axis at their distance of closest approach, and then using the Gaussian relation between antenna gain and distance off-axis.

For example, the r, θ, ε coordinates of the target shown in Figure II.4 may be derived thus

$$r_0 \sin \varepsilon_0 = r_x \sin \varepsilon_x \qquad \text{(constant altitude condition)} \tag{v}$$

$$r_0 \cos \varepsilon_0 \sin \theta_0 - r_x \cos \varepsilon_x \sin \theta_x = x \tag{vi}$$

$$r_0 \cos \varepsilon_0 \cos \theta_0 = r_x \cos \theta_x \cos \varepsilon_x \; . \tag{vii}$$
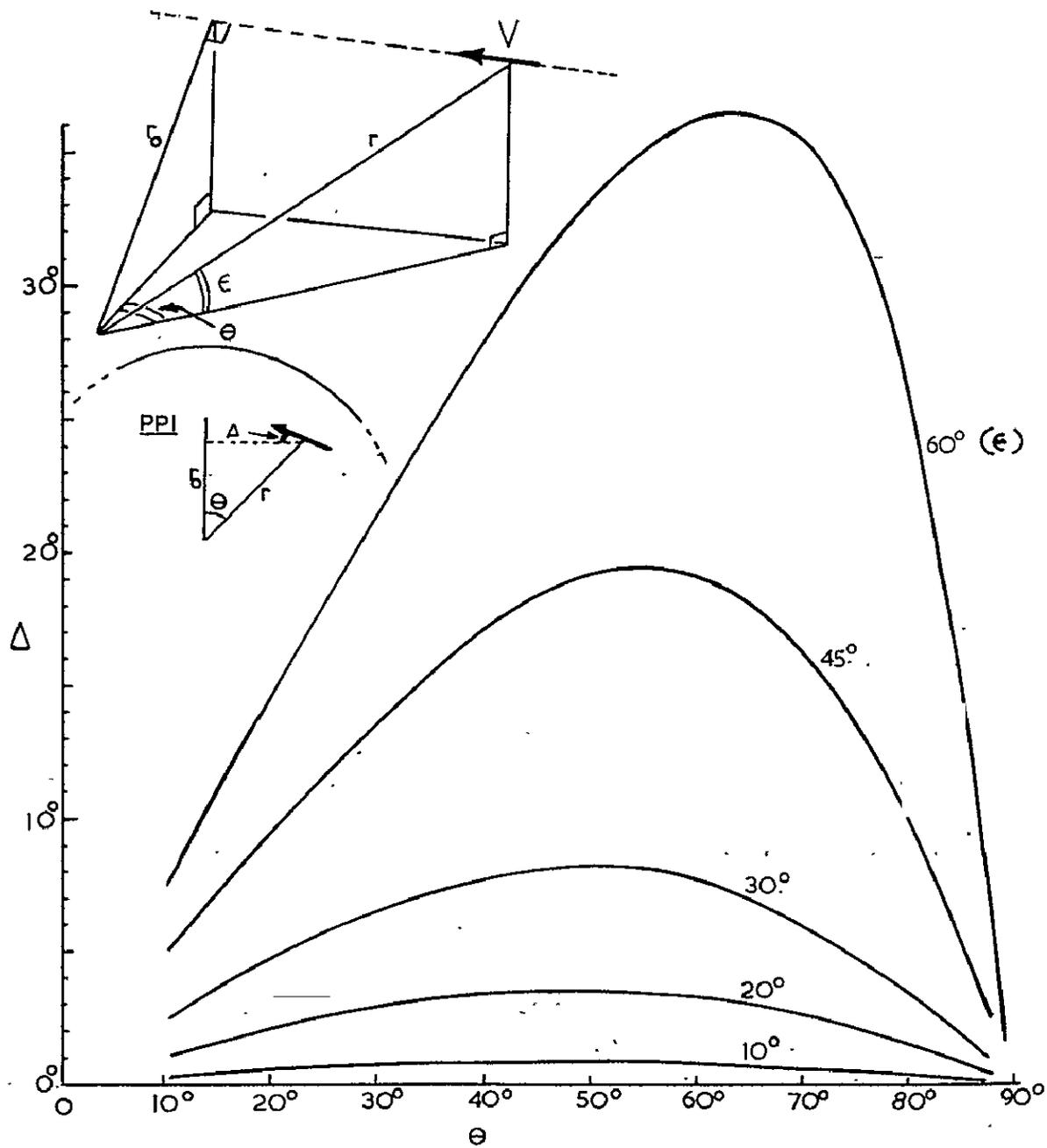
Figure II.2. The apparent direction of movement on a PPI display of a target moving in a horizontal straight line, varies with target position and elevation (ϵ). This graph shows the angular deviation (Δ) of the apparent direction, from the true direction, for a selected series of elevations. The 'true direction' is at right angles to r_o, the vector defining the distance of closest approach. The bearing angle θ, is measured between projections onto a horizontal plane of the target position vector r, and r_o.
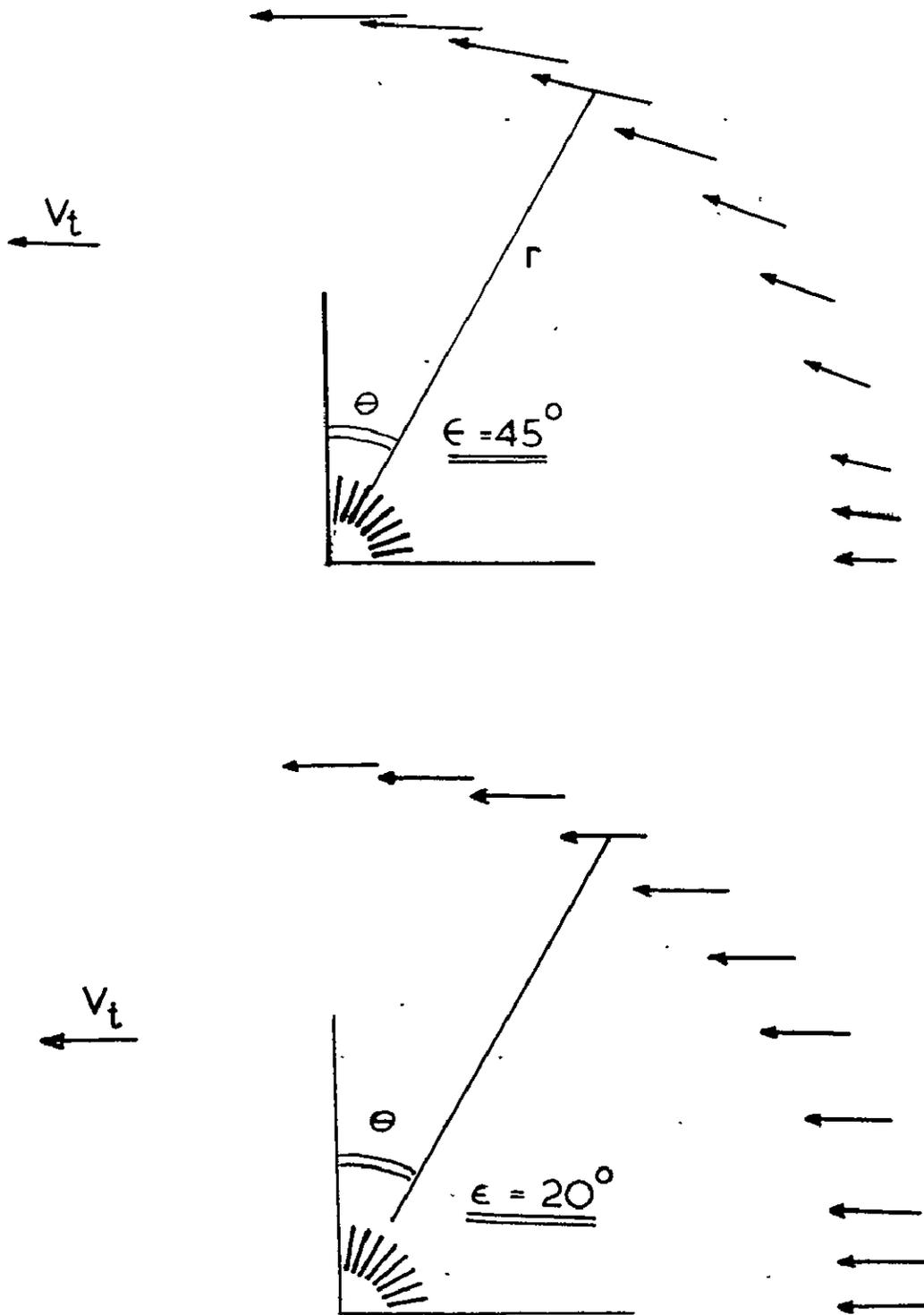
Figure II.3. Examples of the distortion of straight line horizontal trajectories
displayed on a PPI system operating at finite angles of elevation
(ϵ). The velocity vectors indicate the displayed velocity at various
bearing angles (θ). The true velocity is indicated by V_t.

from (vi) and (vii),

$$\tan \theta_x = \left\{ \frac{\sin \theta_0}{\cos \theta_0} - \frac{x}{\cos \varepsilon_0} \cdot \frac{1}{\cos \theta_0} \cdot \frac{1}{r_0} \right\}$$

$$\theta_x = \tan^{-1} \left(\tan \theta_0 - \frac{x}{r_0} \cdot \frac{1}{\cos \varepsilon_0 \cos \theta_0} \right) \tag{viii}$$

from (v) and (vii),

$$\frac{r_x}{r_0} = \frac{\cos \varepsilon_0 \cos \theta_0}{\cos \varepsilon_x \cos \theta_x} = \frac{\sin \varepsilon_0}{\sin \varepsilon_x}$$

so

$$\varepsilon_x = \tan^{-1} \left(\tan \varepsilon_0 \cdot \frac{\cos \theta_x}{\cos \theta_0} \right) \text{ with } \theta_x \text{ from (viii)} \tag{ix}$$

except for $\theta_0 = 90°$, when

$$\varepsilon_x = \tan^{-1} \left(\frac{r_0 \sin \varepsilon_0}{r_0 \cos \varepsilon_0 - x} \right)$$

Thus the maximum signal returned when the beam intercepts the target is

$$S_x = S_0 \left(\frac{r_0}{r_x} \right)^4 \cdot \exp \left(-2.776 \frac{\theta^2}{\theta_{3dB}^2} \right) \tag{x}$$

where S_0 is the signal returned at range r_0. Using (v) this becomes

$$S_x = \left(\frac{\sin \varepsilon_x}{\sin \varepsilon_0} \right)^4 \cdot \exp \left[-2.776 \left[\frac{\varepsilon_x - \varepsilon_0}{\theta_{3dB}} \right]^2 \right] \text{ with } \varepsilon_x \text{ from ix.}$$

S_x is plotted in Figure II.4 as a function of x, for a variety of values of θ_0 (azimuthal position), and it can be seen that the <u>distance</u> along the +x to -x trajectory for which the signal is above a threshold (say $S/S_0 = 0.3$) is much greater for $0 < \theta_0° < 25°$ (i.e. tangential targets) than in other quadrants. Thus the chances of producing enough "hits" on a passing target to produce a measurable trajectory are greater if the target passes along a tangential rather than radial path. The bias is not a serious problem if targets are equally distributed around the radar, because no particular direction of flight is favored.

A more serious bias is generated by target displacement speed. During the time that a target moves along an axis -x to +x, the radar beam rotates several times, producing several hits. If the translation velocity along x is high, the time available for beam rotations is reduced, so the number of hits, and therefore the chances of producing a measurable trajectory are also reduced. It is clear that measurements, for example, of

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the proportion of down-wind orientated (and therefore faster) targets are therefore biased
in favor of the slower, up-wind targets. Allowance can be made for this bias by measuring
trajectory velocities, and correcting the distribution accordingly.

The most serious bias of all is caused by the fact that most insect targets do not
scatter isotropically. Thus in equation (x) one has to include a term which recognizes
the aspect dependence of the target cross.section, $\sigma(\phi)$. We write

$$S_0 = \left(\frac{\sin \varepsilon_x}{\sin \varepsilon_o}\right)^4 \cdot \exp\left[-2.776\left(\frac{\varepsilon_x - \varepsilon_o}{\theta_{3dB}}\right)^2\right] \sigma(\phi)$$

The angular variation of cross-section of *Locusta* may, for example, be approximately
described by the relation

$$\sigma(\phi) = 2.4\left[2.7\left(\exp\left(-\frac{2.78}{14}\phi^2\right)\right) + 0.2\right] \quad [cm^2]$$

This equation has been used with equation (x) to compute the curves shown in
Figure II.5, which illustrate the complex relation between signal strength, heading
and angular position. Unless the target's angular variation of cross-section is
known, quantitative correction for this biasing effect is not possible.
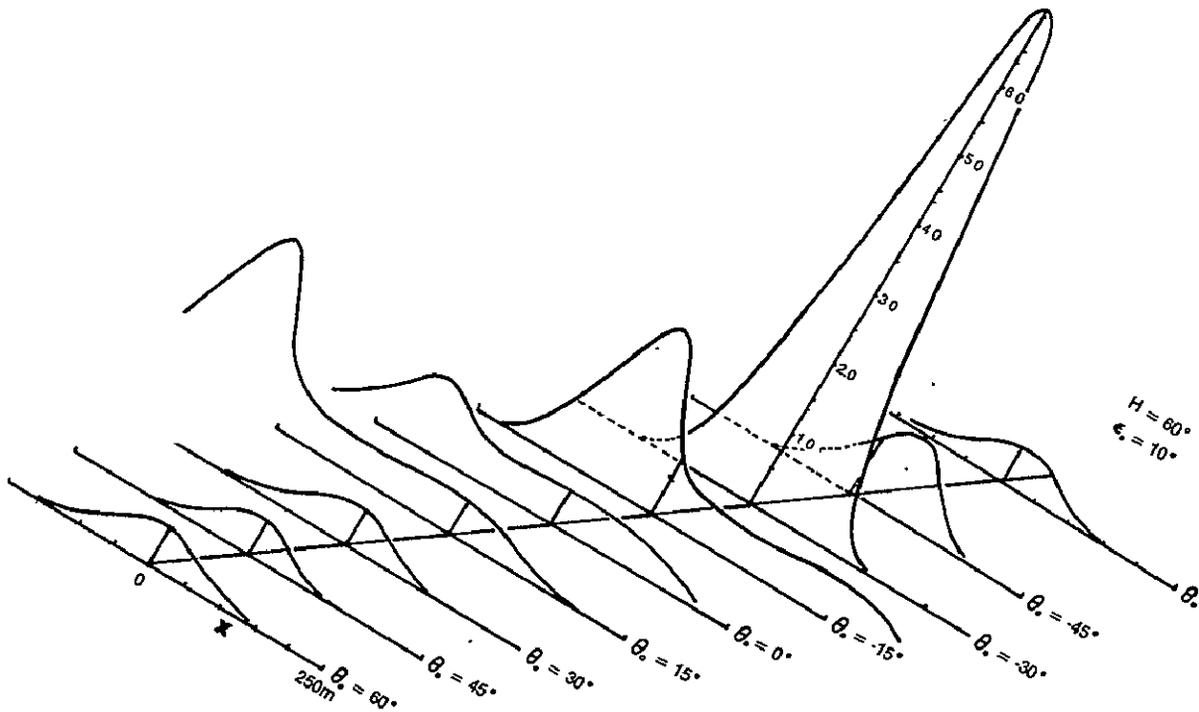
Figure II.5. Graphs showing the radar signal returned by anisotropically scattering targets when they are intercepted by a conically scanning Gaussian beam (3dB width = 1.7°) during horizontal flight past the radar. The targets are assumed to have an air speed equal to the wind speed and to have a common heading (H) relative to the wind direction. The angular variation of cross-section is assumed to be of the form:

$\sigma = 2.4\ \{2.7\ \exp\ (2.8\ \frac{\phi^2}{14}\ )\ +\ 0.2\}$ cm^2 which approximately describes the variation observed in <u>Locusta</u>. (ϕ is the angle between normal to the body axis and the position vector.) Vertical axis shows ratio of signal to that returned by a 1 cm^2 target at r_o, θ_o, ϵ_o (see Fig. II.4).

RADAR PROGRAM AT WESTERN COTTON RESEARCH LABORATORY

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ABSTRACT

The U. S. Department of Agriculture is assembling an entomological radar similar to those used in England. The radar will detect insects in flight and the data will be used for studying insect dispersal.

PROGRAM

The Western Cotton Research Laboratory at Phoenix, Arizona has obtained equipment for a mobile radar to provide information on insect dispersal and migration.

Our laboratory is located in an arid climate and the number of economically important airborne insects near agricultural fields is relatively large compared to the surrounding desert. This is a primary consideration for initial radar studies because noneconomic targets should be fewer than in a more mesic climate.

The radar we are starting with is an X-band marine radar made by Decca of England. It is similar to the entomological radars employed by Drs. J. R. Riley (1) and G. W. Schaefer (2) for insect detection in England, Africa, and Canada. It has a pulse repetition rate of 850 to 3400 pulses per second and pulse lengths from 0.05 to 1.0 microsecond (depending on range scale being used). The logarithmic receiver has automatic tuning, 10 db noise factor, and a performance monitor that will detect a performance decrease of less than -10 db. The range scales vary from 0.25 to 48 nmi. This equipment is trailer-mounted and the antenna turning gear is from an army surplus T-9 radar (part of a 75-mm skysweeper antiaircraft gun). The original 32-inch-diameter reflector will be replaced with a 48-inch reflector. The antenna rotation will be reduced from 60 to 20 rpm and its elevation controlled by a hand wheel inside the trailer where elevation angle will be displayed on a digital readout. The radar display will be photographed with either 16-mm or 35-mm cameras.

To date, the system has been operated with the original radar dish. We only detected ground clutter and aircraft due to the poor location and wide beam width.

Since the atmosphere is the medium used for insect dispersal, we will also monitor meteorological processes with conventional surface instruments and a tethersonde (Atmospheric Research Inc., Boulder, Colorado) mounted on a tethered balloon. This device telemeters profiles of wet and dry bulb temperatures, wind speed and direction, and pressure (i.e. altitude) to a receiver on the ground during both ascent and descent. Atmospheric structure will be monitored with an acoustic radar and then correlated with the distribution of insects detected by the radar.

Additional insect data will be obtained using night vision goggles and various traps on the surface and in the air.

In the future, we hope to acquire additional equipment such as spectrum analyzer, recorder, improved antenna positioner, and shorter wavelength radar.

REFERENCES

1. Riley, J. R., 1974: Radar Observations of Individual Desert Locusts. Bull. Entomol. Res., pp. 19-32.
2. Schaefer, G. W., 1976: Radar Observations of Insect Flight. Insect Flight, Blackwell Scientific Publications, London, pp. 157-196.

THE NASA RADAR ENTOMOLOGY PROGRAM AT WALLOPS FLIGHT CENTER

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The NASA Wallops Flight Center program in radar entomology just started this year. At present there are no field results to report; I hope there will be by the end of this summer. Instead I will say a few words about why NASA is involved with radar entomology and what I envision will be the NASA contribution. After this workshop is over I will likely have new ideas concerning potential NASA contributions. That, in fact, is one of the motivations behind my joining, as a representative of NASA, with the USDA to sponsor our meeting here this week.

As you can gather from what several of the previous speakers have said NASA has developed a large inventory of highly sophisticated equipment and related technical competence as part of the space program. NASA recognizes that much of this technology, the associated skilled personnel, and various specialized facilities can make important contributions to non-space programs. We have at NASA Headquarters a Technology Transfer Division, within the Office of Space and Terrestrial Applications, that sponsors efforts which promise to become a meaningful part of non-NASA activities. We don't, for these types of efforts, simply want cheerleaders to urge us on, only to pat us on the back when we demonstrate that something can be done. In fact we only seek willing partners that need the results of the NASA effort for their own job, and have the resources to buy and use the technology once NASA demonstrates usefulness and practicality.

Wallops has a wide variety of fixed-site and mobile radars for tracking and surveillance. In addition, there are several 1.87 cm (K_u-Band) airborne surveillance radars. Shown in Table I are the systems that are presently used as part of our range operations. These systems support the regular on-going space activities of NASA. Additional to these radars are several special purpose systems that have been developed for research programs in oceanography and geography.

Within the next year some of these systems will be replaced by more up-to-date systems (using some of those surplus Nike mounts Dr. Skolnik mentioned), and a new system that may be of considerable interest to radar entomology will be added. This system will also use a Nike mount with an 8 mm (K_a-Band) monopulse tracking radar.

My estimate at present is that the greatest contribution NASA can make to radar entomology is to use these systems to develop specifications for future entomological radars that the USDA and others can then purchase. Two areas where Wallops can contribute

TABLE 1. SYNOPSIS - WALLOPS FLIGHT CENTER RADARS

Radar	Wavelength (cm)	Peak Power Output (watts)	PRF (pps)	Beamwidth	Antenna Dia. (m)	Antenna Gain (db)	Min. Range (m)	1 M² Skin Track (km)	Range Precision (m)	Angle Precision (rms) millirad.	Polarization
AN/FPQ-6	5.5 (C-Band)	3M	160,640 others available	0.39°	8.84	51	550	1300	±3 rms	±.05	L_V, C_L, C_R
AN/FPS-16	5.5 (C-Band)	1M	160,640 others available	1.24°	3.66	43	275	350	±3 rms	±0.1	L_V
AN/MPS-19	10 (S-Band)	325K	160,320,640 & 1280	3°	2.44	33	225	100	±10 rms	±1	L_V, L_H
Mariners Pathfinder	3.2 (X-Band)	40K	1K,4K	0.6°	3.7 L	N/A	20	30 (ships)	N/A	N/A	N/A
SPANDAR	10 (S-Band)	5M	160,320,640	0.39°	18.3	52.8	900	2250	±5	±1	L_V, L_H, C
RARF	7 (UHF)	8M	320 - 960	2.9°	18.3	36	225	1500	N/A	±2	L_V,L_H -
RARF	10 (S-Band)	5M	320,960	0.39°	18.3	52.8	N/A	1500	±.1%	±1	L_V
RARF	3.2 (X-Band)	1M	320	0.2°	9.1	50	N/A	1500	N/A	±2	L_V
AN/ASR-7	10 (S-Band)	425K	1200,713 others available	csc^2	9x17 2.7x5.2	N/A	N/A	75 (aircraft)	±1%	N/A	L_V, L_H, C
AN/FPS-16 (Runway)	5.5 (C-Band)	1M	160,640	0.71°	4.8	46	N/A	N/A	±3	±0.1	L_V, C_R
AN/GSN-5	.86 (K_a-Band)	75K	2K	0.99°	1.22	48.5	150	45	±3	±0.3	L_V, C
AN/MPS-19 Mobile	10 (S-Band)	325K	300 - 2000	3°	2.44	33	200	100	±25	±1	L_V, L_H
ASR-9437	1.87 (K_u-Band)	140K	400,1600	1.3°	2x3.2 0.6x1.0	37	N/A	220 (ships)	N/A	N/A	L_H

over the next few years are in data recording, processing and display, and by investigating the effectiveness of various radar wavelengths for insect studies.

The first figure shows a simple K_a-Band radar mounted on an old searchlight mount. Although this particular radar is on loan to Wallops, the subsystem we are having developed will be used later with various other radars. Control of the radar, along with signal processing and data recording, will be done through a Hewlett Packard 9845 minicomputer that can be installed in a separate van. Also not shown is the power generator. The Johns Hopkins Applied Physics Laboratory, which has been a contractor to WFC for many years, has designed and will put together the complete minicomputer based radar subsystem.

This subsystem is very important. Although the exact operator selectable controls that the computer will provide have not been specified, considerable flexibility in choice of spatial scanning pattern - both in angle and range - can be provided. The operator can use the radar in a traditional surveillance mode - limited only by certain restrictions in the mount - or, through commands from the computer console, he can select restricted regions for increased sampling. In other words, we will have a system in which we have console control of the spatial sampling strategy. In addition, the computer receives position and backscattered power data from individual targets and processes the data for display in real-time on an x, y, z scope. Printout onto paper copy is also available.

The computer also controls the digital recording that can be done. There will be a disc storage unit that receives digital data from selected samples. We will also have a video recorder with 5 MHz bandwidth for continuous recording.

The level of funding for next year is uncertain at present; however, with sufficient funding the system can be made mobile and taken to appropriate field locations where insects are active. Present plans call for joint field observations with the USDA X-band (described in the previous paper by Wayne Wolf) and the WFC K_a-band systems so that system comparisons can be made.

One activity that WFC can contribute to almost immediately is in radar signature analysis of single insects at C and S-Band (5 cm and 10 cm). Figure 2 shows an aerial view with the Spandar in the foreground and Q-6 farthest away. The high precision and versatility of these radars, along with excellent support facilities, will be useful for studying power returned from insects as a function of wavelength, polarization, aspect angle and some characteristics of flight such as wingbeating. At the same time we will be able to correlate these observations with temperature, time of day (or night), and wind velocity. We already have considerable experience with such studies using birds as targets.

Figures 3 and 4 show previously unpublished results from a program I ran to develop species identification techniques for birds. From 1969 through 1973 ornithologists showed great interest in the Wallops radars for studying bird migration. Such studies basically involved tracking individual migrants as they passed the radar. These were night migrants;
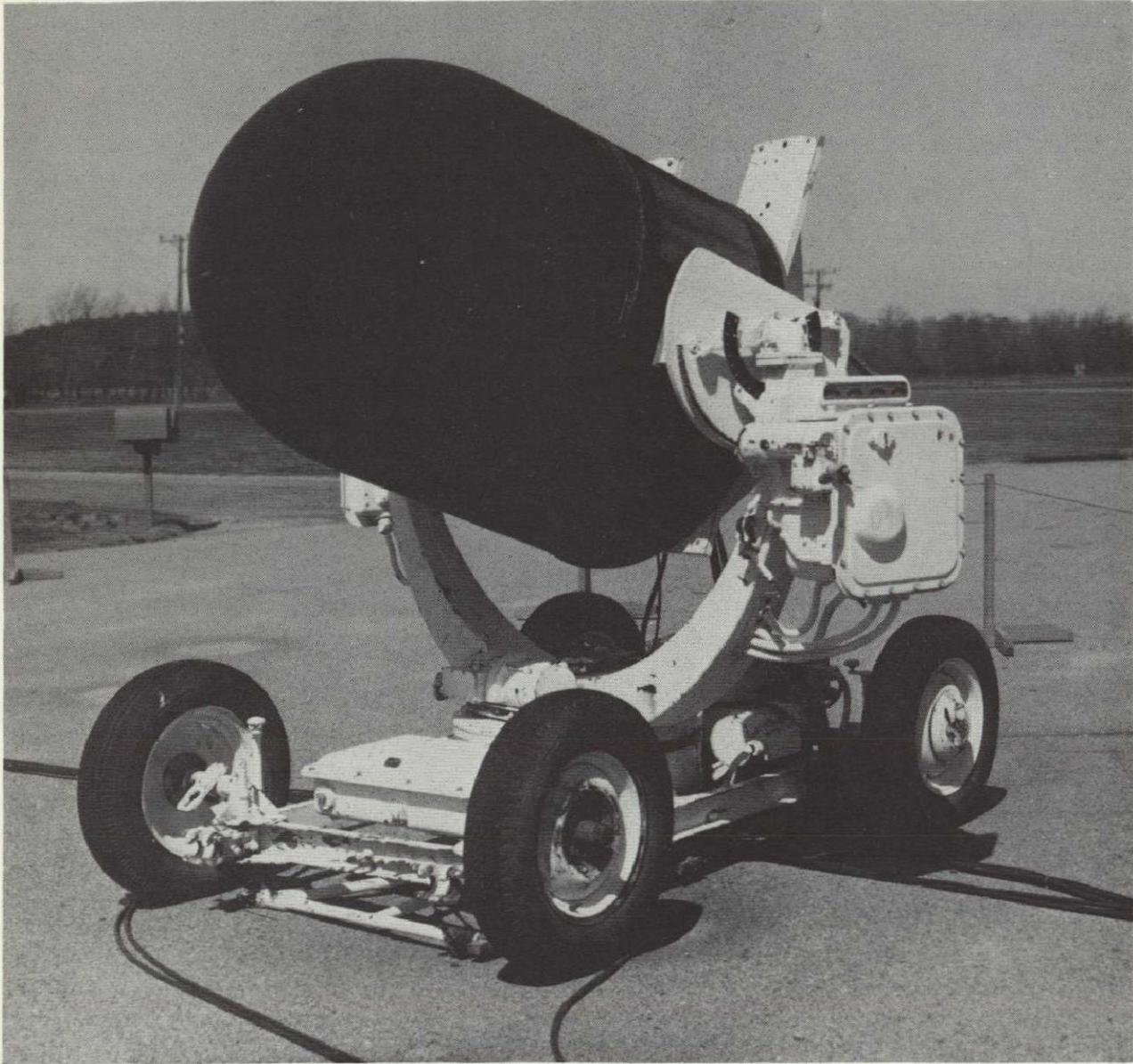
Figure 1. A LAPQ-1 35 GHz radar mounted on á surplus searchlight mount.
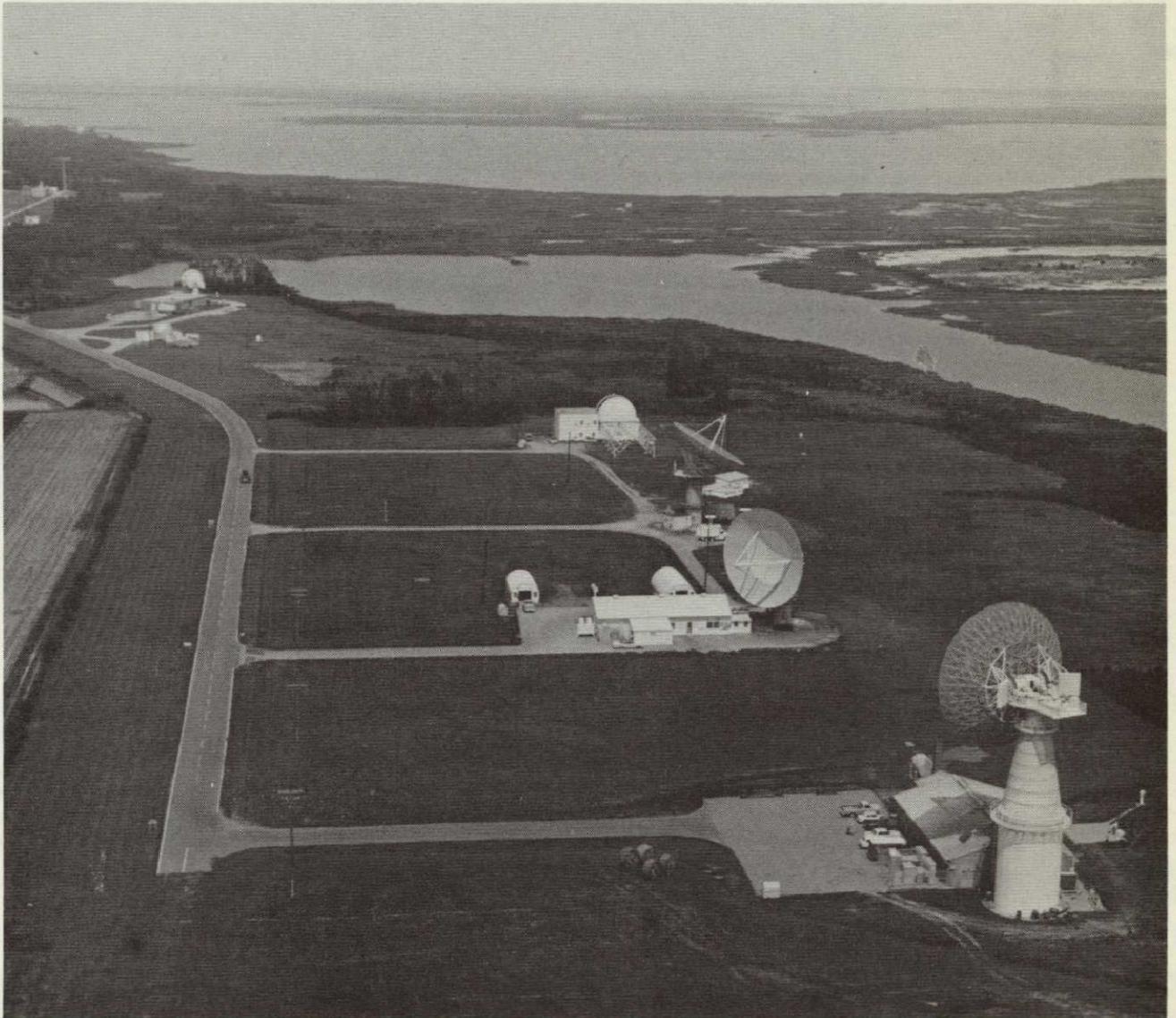
Figure 2. Aerial view of the Mainland radars at Wallops Flight Center.
The S-band Spandar is in the foreground. In the background
to the left is the Q-6 high precision tracking C-band radar.

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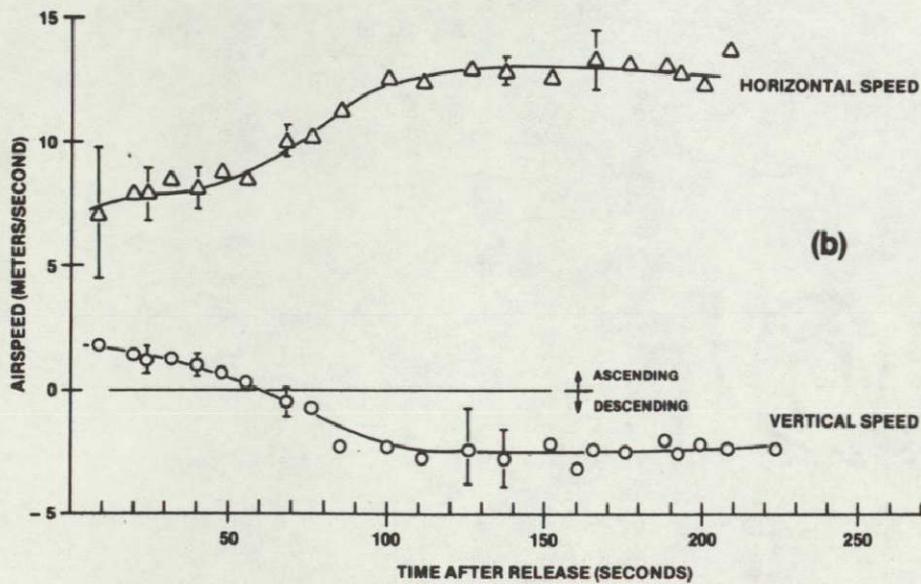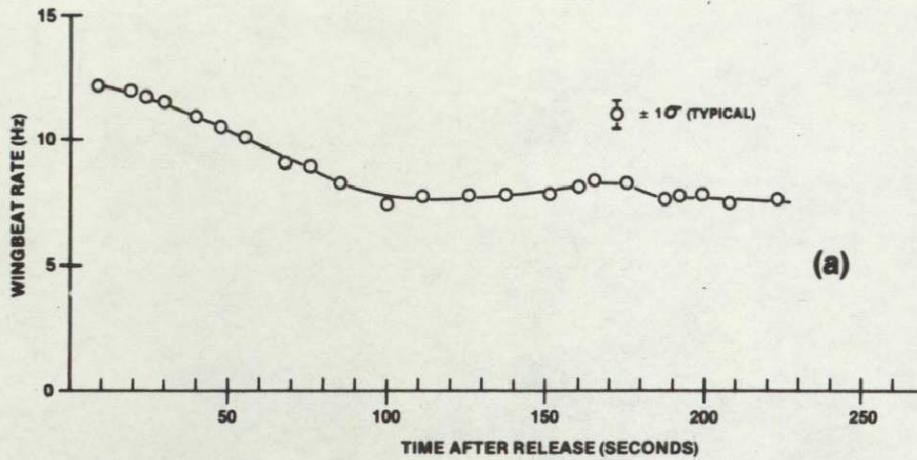
Figure 3. Parameters determined from radar tracking of bird released at
night from helicopter. Vertical bars on data for airspeed
indicates one standard deviation for typical points.

VERTICAL SPEED
VS
WINGBEAT RATE
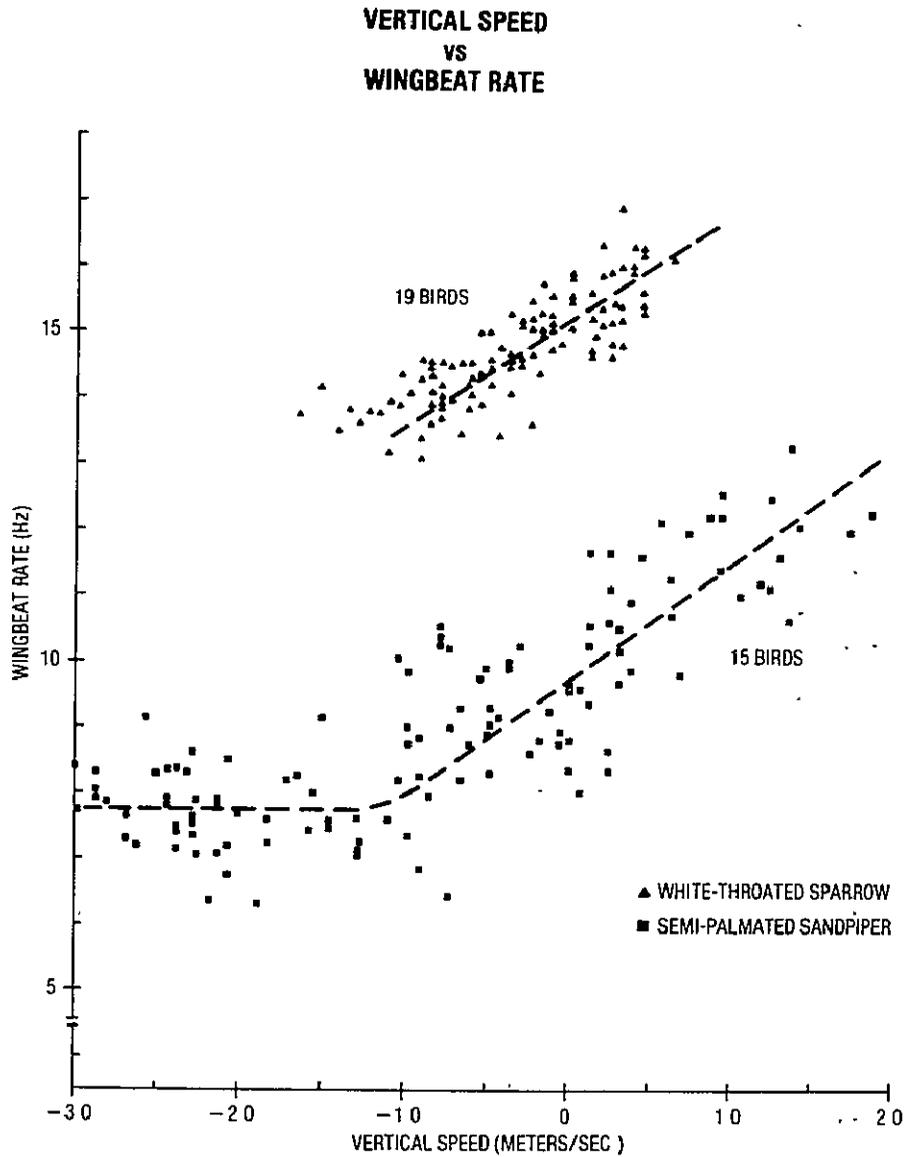
Figure 4. Two species of birds released from helicopter and tracked by
radar. Data for each vertical speed is from a five point
average over five seconds of track.

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and, they would often not come within 5 to 10 kilometers of the radar. There was no way to know what species was being tracked. I used a helicopter to release known species for tracking, so that a radar "signature" catalog could be developed. I had relatively high resolution tracking data, and radiosonde balloons were released each evening. Therefore I could determine the airspeed of each released bird.

Figure 3 is typical of the way the wingbeat rate and horizontal and vertical air-speeds of many released birds varied with time. The relevant point for our purposes is that 3(a) is also qualitatively the same as results that other investigators have found for birds (ref. 1) and insects (ref. 2). These other studies, though, have not included tracking data. However, as we see from 3(b), such data indicates that the changing wing-beat correlates with horizontal and vertical air speeds. Such a result was also found with a bat (ref. 4) constrained to fly horizontally in a wind tunnel.

Figure 4 removes the artifact of time by combining data from many individuals of each of two species. (Actually the "semipalmated sandpiper" data include some from western sandpipers - these species are almost indistinguishable in size and shape.) There are no previously reported data of this nature in the literature. I have done a preliminary theoretical analysis that includes the vertical flight component of the data. It turns out that simple constant parameters in the physical equations for flight can reproduce the semipalmated sandpiper curve from a vertical speed of -2 m/s to + 1.5 m/s.

Figure 4 also shows data for a white-throated sparrow. In the power versus time histories (not shown here) of individual birds, we can see the flap-pause wingbeating typical of many species of passerine birds. The instantaneous wingbeat rate is shown on the figure as a function of vertical speed. Notice that again the wingbeating decreases with rate of descent - almost as dramatically as with the previous species. Emlen (ref. 3) also studied this species but shows vertical airspeed versus percentage of time beating. His result is qualitatively similar to mine. However, if we assume a constant instanta-neous wingbeat rate for Emlen's birds, the mean wingbeat changes by almost a factor of two as the vertical speed changes from -1.0 m/s to + 0.5 m/s. Since the instantaneous rate also decreases with rate of descent, as shown in Figure 4, the real time averaged wingbeat varies over a larger factor. It is thus evident that a complete analysis of my data, using mean wingbeat rate averaged across pause periods, will show a more dramatic effect than that in Figure 4.

Because Emlen finds a wide scatter in his data - more so than in the data I present - he concludes that intraspecific variability in a species' parameters precludes fine inter-specific differentiation. I think such a conclusion premature. From Figure 4 we see that wingbeat rate, in the linear region of both curves, changes about 1.8 Hz/meter/sec. With the radar used, and at the tracking range of the birds, it is extremely difficult to determine vertical speed with the accuracy required to determine the cause of the data scatter. In many cases a measurement error of ± 0.25 to 0.9 m/s, which could account for

the major portion of the scatter in Figure 4, is reasonable.

It is not the purpose of this talk to discuss the flight of birds so I won't dwell on this any longer. The point I hope to make is that when we start to work on a problem - such as insect species identification by radar - we should use the most precise instruments available to collect data, and we should choose instruments that will provide as complete a picture of what's going on as we can get. Later we can decide if less data are needed.

We shouldn't draw too hasty conclusions about what radar can, or can't, tell us about insects (or birds). Birds have been studied a number of times using tracking radars. The statement is often read that we can't identify birds to species using radar. I think there has been insufficient work to say that. It has proved next to impossible, to date, to develop experimental techniques that allow us to know our target and its behavior with certainty, independent of the radar observations. Such knowledge is necessary to confirm the interpretation of the radar data. The only thing that has been done is to show that one or two observable parameters are insufficient for the task. Whether entomologists can do better than ornithologists will depend partly on the extent they are willing, or capable, of pursuing the problem. Wallops Flight Center has the radar facilities to help in this endeavor. I hope there will be sufficient interest that we can do so.

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REPORTS FROM WORKSHOP GROUPS

I. ENTOMOLOGICAL RESEARCH

Participants: Robert Jackson, Chairman

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C. Purdy	R. Rabb	J. Riley
W. Ruesink	J. C. Webb	

INTRODUCTION

The most effective and ecologically sound pest management strategy for a highly mobile pest involves management of the total insect population. However, the lack of a comprehensive understanding of the effect that insect movement has on the population dynamics of any particular species seriously limits the usefulness of a total population pest management system for that species. Until ignorance of insect movement is overcome, both qualitatively within the overall life history of an insect population and quantitatively in a particular field situation, total population pest management systems cannot provide adequate pest control.

The following research outlines are not meant to provide an exhaustive list of research which could be appropriately addressed through the use of radar technology. Rather, these outlines represent examples of research problems which are uniquely suited for investigation with radar technology and which can not be readily solved with other techniques.

I.1 Usefulness of Radar Technology in Insect Population Dynamics Studies

Objectives:

1. To determine the applicability of radar technology to understanding Lepidopteran (*Noctuidae*) dispersal and/or migration in the SE United States. This involves determining the usefulness of radar to:

   a. detect and quantify short range (field-to-field) movement;

   b. detect and quantify net displacement of multi-species complexes;

   c. derive species-specific radar signatures, thus allowing simultaneous monitoring of key species.

2. To determine the usefulness of radar technology in calibrating commonly used methods of measuring relative insect densities (e.g., light and pheromone traps).

3. To resolve the most appropriate timing of the use of radar technology, i.e., is radar most useful before, during, and/or after detailed population dynamics studies of target species.

4. To resolve the time frame necessary to overcome communication gaps between entomologists and radar specialists.

Justification:

Several species of noctuids inhabit various proportions of the SE United States and cause hundreds of millions of dollars in damage to cropping systems that include corn, peanuts, soybeans, cotton, tobacco and vegetables. Other crops can suffer to a lesser degree. Among the damaging insects are the fall armyworm, beet armyworm, velvet bean caterpillar, corn earworm, tobacco budworm, soybean looper, and cabbage looper. These species occupy a wide variety of habitats, depending upon crop mix, crop phenology, and weather.

Basically, there are two potential "life styles" used by members of this complex. The first involves pupae overwintering in northern zones where adults can't survive the cold weather. Such overwintering follows a period of feeding, mating, dispersal, and oviposition.

The second life style involves species that only survive in warm climates during winter and undergo uninterrupted breeding on one or several native or agricultural plants. These species expand their distribution by dispersing northward as temperatures begin to warm in late spring and early summer. Our present understanding of the population biology of these species is inadequate because we lack even a qualitative understanding of the role of movement in their population dynamics. Application of an effective technique to detect and measure movement would constitute a breakthrough that not only would lead to increased predictability of target species dispersal, but also would lead to more fruitful studies of other organisms.

The Noctuids in question infest millions of acres of cropland in the USA and inflict millions of dollars in annual losses. Integrated pest management strategies to combat these pests are severely limited primarily because of a lack of understanding about their movement. Radar can serve as a powerful tool to aid in understanding these dispersal movements.

Accomplishment of the proposed objectives is no mean task. A detailed timetable for program activities needs to be designed to insure the best compatability of radar field measurements with population dynamics studies on target species. Studies should be designed to investigate both local and dispersal movements within the context of the population dynamics studies. Since insect dispersal modelling will require specific types of data, radar observations should also be coordinated so that both primary and validation data can be obtained for model development.

A considerable quantity of population dynamics information on target species already exists and must be assembled prior to testing of radar technology. In addition, though, much preparatory field information on the population dynamics of any particular target species needs to be acquired in the specific area where field tests are to be conducted. The following plan outlines the steps of a proper experiment in population biology that is necessary for the design and evaluation of a radar technology application experiment.

Year 1

1. Initiate a major literature search on population dynamics studies of target species.
2. Design experiments to determine:
    a. Host plant distributions of target species.
    b. If instrinsic control of movement is similar for adults of each generation; if not, how does it vary?
    c. If variation in intrinsic control results in a recognizable difference in movement (suggesting both trivial and long distance movement)?
    d. How widely individuals of each generation disperse.
    e. The effect weather has on timing, distance, and direction of movement.
    f. Specific dispersal behavior patterns of adults with varying ages, generations, and host origins.
    g. Specific behavior patterns of Noctuids if (a) eclosion is from fields of different host plants under warm-clear, warm-cloudy, cold-clear, and cold-cloudy conditions and (b) adults of all ages are exposed to high altitude, long-distance displacement.
3. Conceptualize specific experiments involving radar in areas where sufficient biological data on target species exists (e.g., comparing radar counts at various altitudes with insect counts in several crop systems).

Years 2-10

1. Conduct experiments as designed in year 1.
2. Update experiments as jointly determined necessary by radar specialists and ento-
   mologists.
3. Continue specific radar/entomology experiments like (3) above.
4. Integrate, where possible, radar technology into the seven experiments designed in
   year 1. Do this only when both entomologists and radar scientists deem the results
   potentially to be worth the efforts.

Years 7-10

1. Based on results from years 1-7, the range of applicability where radar can aid in
   the understanding of target species dynamics can begin to be narrowed (or expanded).
2. Concentration should then be maintained on precise uses of radar as discussed in (1).

Post Year 10

If determined worthwhile, incorporate radar into standard IPM biological monitoring pro-
grams or use radar until adequate dispersal models not requiring inputs from radar are
assembled.

I.2 Insect Transport Model Development

Objective:

To develop verified mathematical models that describe the small and large scale movements of airborne insects.

Justification:

In general, a well-designed model is cheaper to run than a field program to answer the same questions. Models also help scientists to organize data and ideas when there is a large body of knowledge. Finally, models can be used for assessment and prediction purposes.

A comprehensive transport/diffusion model for airborne material requires both field observations to evaluate parameters and formulate processes in the model, and an independent set of field data to verify the model. In addition, for a given application of the model, field data are required to determine boundary and initial conditions. Hence, there is a strong coupling between field observations and modeling.

A well-constructed, verified insect transport model can be used to determine the impact of land use changes on the airborne movement of insects, assess the effects of pest management practices, and study the interaction of airborne living species and air pollutants or insecticides. Models can be used to predict (not on a real-time basis) future events, such as the migration of pests. Finally, models can be used for the real-time prediction of movements of insects over local and mesoscale ranges for time periods of 3 to 72 hours.

Radar is useful in three ways to modelling activities; first, as a data source for model building; second, as a tool for model verification (i.e., by observing the future state); and third, as a sensor for gathering necessary data to start the model (boundary conditions) and later (in time) to verify the accuracy of the model during field use.

APPENDIX

AN INSECT TRANSPORT MODEL

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INTRODUCTION

Insect population ecologists and pest management scientists are concerned with many elements of an insect's life cycle, as an individual and as a member of a population. The focus of this report is on the movement and fate of insects through the atmosphere, and how these movements affect and are affected by other activities of the insects, more specifically, this report focuses on the construction of an insect transport model that can be used to understand and to predict the movement and fate of airborne living species. A model of this type will require entomological and meteorological data to properly determine the formation of velocity fields, diffusion fields, and the characteristics of sources and sinks. The sources for this model are characterized by the type, number, and form of insects being emitted into the airways, while the sinks are any processes removing the insects from the atmosphere. Once the model is properly formulated and verified, it can be used to plan further field experiments, to predict the airborne aspects of future outbreaks, and to understand the airborne component of the insects' life cycle.

The transport of insects over meso- and macroscales is a result of complex interactions between atmospheric flows of various scales and intensities; terrain effects such as mountains, lakes and oceans, wooded areas and urban regions; weather systems such as frontal activity, thunderstorms, and large air mass movements; and a variety of insect activity, such as insect communications, the energy balances around individual members and the aerodynamic control mechanisms applied by the insects during transport. To realistically model this type of transport requires all the usual information concerning the transport and diffusion properties of the atmosphere plus information about the insects' activity, physical and physiological characteristics, and origins. Since there is much research that must be completed before a realistic model can be constructed, the following discussion will treat insect transport modeling in a general fashion and will conclude with specific recommendations for future research.

TERMINOLOGY

Scales of Motion

In the atmosphere there are many scales of motion that influence the transport and diffusion of particles, in general, and insects, in particular. The important horizontal scales that influence insects are:

- <u>Local</u>. From meters to 10 - 20 km.
- <u>Mesoscale</u>. From 10's of km to 100 - 200 km.
- <u>Regional or Macroscale</u>. From 100's of km to 1000 - 2000 km.

The important vertical scales or divisions that influence insect movement are:

- <u>Surface Layer</u>. From the earth's surface to 50 to 100 meters.
- <u>Planetary Boundary Layer (PBL)</u>. From the earth's surface to 1000 to 2000 meters.
- <u>Troposphere</u>. From the earth's surface to 10 to 12 km.

The time scales that correspond to these vertical and horizontal space scales are:

- Seconds to minutes.
- Minutes to hours.
- Hours to a day.
- Several hours to several days.

Terrain Features

The atmospheric transport and diffusion characteristics are highly dependent upon the ground cover and terrain features, especially in the surface layer and PBL. The surface layer is the region where the insects are emitted into the air stream and may be the area which contains the major part of the flight paths.

The terrain and cover features may be classified as follows:

- <u>Homogeneous, Flat or Rolling</u>. The terrain is flat or slightly rolling and the ground cover is homogeneous, such as all grain fields, all woods, or all grasslands.
- <u>Nonhomogeneous, Flat or Rolling</u>. The terrain is flat or slightly rolling but the ground cover is nonhomogeneous, such as land/water interfaces, areas of grasslands and forests, urban and rural regions, and cornfields surrounded by grasslands.
- <u>Simple Terrain Features</u>. Examples of simple terrain features are isolated hills, single river valleys, a long ridge, and sharp-edged cliffs.

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- <u>Complex Terrain</u>. Complex terrain consists of many mountains and valleys at various orientations.

Frames of Reference

In the analysis of the transport and diffusion of material, such as insects, models are referred to some type of spatial grid system. This reference frame may be fixed at the earth's surface, or at the center of mass of the airborne cloud of insects. The former case is called an Eulerian frame of reference and the latter case is called the Lagrangian frame. The Lagrangian frame moves with the cloud of insects and represents an observer watching the insects while "flying" along with them. The Eulerian frame represents an observer standing on the ground watching the insects move through the air. From the radar point of view, a fixed ground-based radar observes the insects from an Eulerian frame, while an airborne radar system flying along with the insects observes from a Lagrangian frame. For modeling purposes, mixed Eulerian/Lagrangian systems are sometimes used.

The independent variables in an Eulerian system are the spatial coordinates $\underline{x} = (x,y,z)$ and time t. For the Lagrangian system, the independent variables are the original spatial coordinates of the cloud $\underline{x}_o = (x_o, y_o, z_o)$ and time t. The quantities (x, y) represent the horizontal coordinates and z is the vertical coordinate, positive in the upwards direction. The original coordinates $\underline{x}_o$ may represent the center of mass of the insect cloud as the insects become airborne, or have left the canopy.

STATE-OF-THE-ART OF DIFFUSION MODELING

Since the advent of the Clean Air Act in 1970, there have been a multitude of various types of air quality models developed. Some of these models have been quite successful for their intended purposes, while many others have not been successful. The more complex models are still basically in the development stage, and their various components have not been verified against field data. The state-of-the-art of the quality of atmospheric input data and the validity of transport/diffusion models is given in the following subsection.

Atmospheric Motion

The atmospheric motion is represented by an average wind field denoted by $\underline{V} = (u,v,w)$, where (u,v,w) are the mean wind speeds in the (x,y,z) directions, respectively. For an insect model, the wind fields can be obtained from the National Weather Service or from special field experiments carried out in specific regions. The evaluation of the state-of-the-art for $\underline{V}$ is:

- Regional data for a few hours to a few days - GOOD.
- Mesoscale data for a few hours over homogeneous, level or rolling terrain - FAIR.
- Except for special field programs, data for level, nonhomogeneous terrain and for simple and complex terrain over mesoscale and local scales - POOR.
- Data for regional scales over complex terrain - FAIR TO POOR.
- Physics of the motion in the surface layer and PBL for daylight hours under moderate winds over level or rolling homogeneous terrain - WELL-KNOWN.
- Physics of motion in the surface layer and PBL for nighttime situations and for all diurnal periods over nonhomogeneous and complex terrain - FAIR TO POORLY KNOWN.

Atmospheric Turbulence (Diffusion or Mixing)

Atmospheric turbulence is the ability of the air to diffuse or mix material (such as insects) as the material cloud moves through the air with the mean motion $\underline{V}$. At present, most complex models of the atmosphere describe the diffusion of material with a diffusivity tensor of the form

$$\underline{\underline{K}} = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix} \tag{1}$$

In the well-known Gaussian plume and puff formulas, $\underline{\underline{K}}$ is replaced by diffusion coefficients. The state-of-the-knowledge of $\underline{\underline{K}}$'s or diffusion coefficients is:

- For daylight hours with moderate winds over level or rolling homogeneous terrain, for local areas to the lower limits of the mesoscale, and in the PBL - GOOD TO FAIR.
- For nighttime situations, or for light winds with active convection during hot days over local and mesoscale regions - POOR.

- For most spatial scales and time periods over level nonhomogeneous and complex terrain - POOR.

'ansport Models for Gases and Particles

The current success of transport models is highly dependent upon the input data, such as the wind field $\underline{V}$, the diffusion field $\underline{K}$, and the chemical and physical properties of the gases and particles. The two previous subsections outline the difficulty with obtaining high quality input data for certain scale ranges, diurnal periods, and terrain categories. Even though the present state-of-knowledge is not outstanding, we should not be frustrated but continue to develop better models and to develop field programs to tune and verify the models. The state-of-knowledge of transport/diffusion models is as follows:

- Local and mesoscale models of nonreactive gases and spherical particles in moderate wind conditions over level and rolling, homogeneous terrain - GOOD TO FAIR.
- In general, all other models for all other combinations of scale and terrain categories - IN THE DEVELOPMENT STAGES, BUT ARE BASICALLY UNPROVED.
- Diffusion or mixing of particles in the atmosphere - POORLY KNOWN.

A TRANSPORT MODEL FOR LIVING SPECIES

Suppose we define $C = C(\underline{x},t)$ to be the number concentration of living individuals in a unit volume of air. The quantity t is the time of transit from some initial position and $\underline{x} = (x,y,z)$ are the usual Cartesian coordinates referred to either a fixed Eulerian frame of reference or a moving Lagrangian reference frame. In complex terrain the z-coordinate may be modified to be a terrain-following coordinate, such as normalized pressure surfaces.

The quantity C will be conserved in some domain D of the atmosphere. That is, the local rate of change of C in D plus the outflow from D minus the inflow into D must equal the turbulent dilution of C in D (diffusion) plus the sources of C in D minus the sinks of C in D. The domain D may be a moving Lagrangian cloud or a fixed Eulerian domain. In equation form, this conservation law (or continuity equation for C) is given by

$$C_t + \underline{\nabla} \cdot [(\underline{V} + \underline{V}_I)] = \nabla \cdot [(\underline{K} + \underline{K}_I) \cdot \underline{\nabla}C] + S_o - S_1 \quad . \tag{2}$$

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The quantity C_t is the local time rate of change of C in D, and the second term on the left of (2) is the transport of C through D. The velocity vector $\underline{V}$ represents the wind field in the atmosphere in the Eulerian frame; in the Lagrangian system, $\underline{V}$ is set equal to $\underline{Q}$. Thus $\underline{V}$ carries the information about the flow fields around weather fronts, thunderstorms, and moving air masses; and in addition, $\underline{V}$ is modified by surface roughness and atmospheric stability.

The quantity $\underline{V}_I$ is the mean motion of the insects with reference to a frame moving with velocity $\underline{V}$. In general, $\underline{V}_I$ is a function of the wind field, humidity and temperature, radiation, and insect behavior and physiology. Specifically, $\underline{V}_I$ will include the vertical velocity (or settling speed) of the insects and the propulsion velocity for insects under active flight.

The first term on the right of (2) is the diffusion of C in D, where the diffusivity tensor of the air is given by Equation (1). The corresponding diffusivity tensor for insects relative to the mixing air is given by $\underline{K}_I$. As for $\vec{V}_I$, the quantity $\underline{K}_I$ is a function of $\underline{V}$, humidity, temperature, radiation, insect behavior and physiology, etc. If $\vec{K}$ and $\vec{K}_I$ are assumed to be variable, then (2) represents the usual K-theory approach. On the other hand, if $\vec{K}$ and $\vec{K}_I$ are assumed to be diagonal, constant parameter, square matrices, then (2) represents the Gaussian plume or puff approach.

The quantity S_o represents the source of insects within the domain D, or (through the use of Dirac delta functions) the boundary conditions of C at the earth's surface and the sides of D. The quantity S_I is the sink of insects in D and may be produced by the scavenging of insects by rain, snow, sleet, air pollution, insecticides, extreme changes in temperature, predation, or other processes.

The sources of insects at ground-level, at the tops of canopies, etc. depend on the ground-level concentrations of eggs and insects, insect activity, time of day, meteorology, etc. The sources of insects through the vertical boundaries of domain D depend on the number of airborne insects moving into the region from outlying areas.

The length scales over which the various subclasses of models represented by (2) should be applied are as follows:

- Gaussian plume models for scales up to 10 to 30 km in reasonably uniform terrain.
- Box models (single cell or a small number of multi-cells) for scales up to 10 to 30 km.
- Grid-type, K-theory models for scales up to 100 to 300 km.
- Segmented plume or Gaussian puff trajectory models for scales from 500 to 2000 km.

In Figure 1 we show a schematic of an insect transport model. This figure indicates the various areas of past, present, and future research activities that are important for the construction of a comprehensive transport model for insects. In the following discussion we outline the status of research along the numbered paths shown in Figure 1.
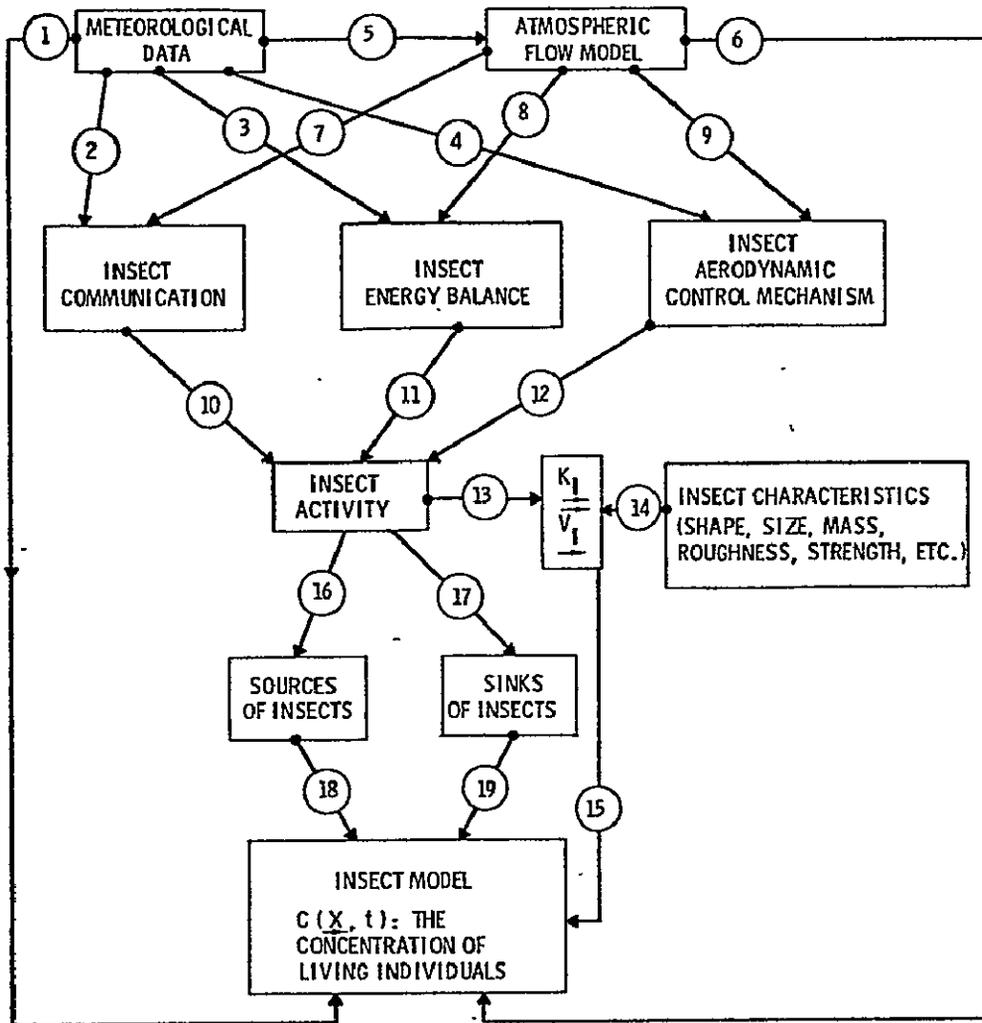
Figure 1. A schematic of an insect transport model.

Paths 1 and 5. The collection of better and more comprehensive meteorological data (such as $\underline{V}$, $\underline{K}$, radiation, humidity, and temperature) is being undertaken by many agencies and is being summarized by the National Weather Service.

Paths 2 and 7. Much research is required to understand the meteorological influences on insect communications.

Paths 3 and 8. Much research is needed on the effects of local meteorology on the energy balance in individual insects.

Paths 4 and 9. Although some insects have been studied in great detail, there is still a general need to assess the influences of meteorology on the aerodynamics of insects.

Path 6. There are rather comprehensive meso/macroscale flow models under development in several programs throughout the country. These models can be used to derive an insect model.

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Paths 10, 11 and 12. The entomologists are currently studying how insect activity, is influenced by energy balances, aerodynamic control mechanisms, and communication devices;· but more work is needed.

Paths 13 and 14. Much work is required to express the parameters $\underset{\rightarrow I}{K}$ and $\underset{I}{\Psi}$ in terms of the insect's characteristics, activity, and meteorological variables.

Paths 16 and 17. Insect activity is certainly an integral part of initiating flight and terminating flight or life in the atmosphere. Entomologists have studied the initiation of flight extensively for many species, but the airborne termination of flight is poorly known.

Paths 15, 18, and 19. Once S_o, S_1, $\underset{\rightarrow I}{K}$ and $\underset{I}{\Psi}$ are properly formulated, the incorporation of these quantities into the insect model, Equation (2), is basically a minor problem.

USE OF RADAR TO EVALUATE MODEL PARAMETERS

For the analysis of specific field experiments, radar can aid in describing the boundary and initial conditions for $C(\underset{\rightarrow}{x},t)$ in both Eulerian and Lagrangian models. In addition, radar can be used to help verify both Eulerian and Lagrangian models through measurements of $C(\underset{\rightarrow}{x},t)$ in domain D at various times and spatial locations. Radar may also be useful in evaluating source and sink strengths. The source strength at the canopy tops may be measured by radar if ground clutter can be properly minimized. The effectiveness of insecticides and air pollution in killing certain airborne insects may be detected by radar if "flight" characteristics of the bugs change significantly.

As ground-based radar follows a cloud of insects, the mean velocity $(\underset{}{\Psi} + \underset{I}{\Psi})$ of the cloud can be determined. By other meteorological instrumentation we can determine the wind velocity $\underset{}{\Psi}$. Hence, we can determine $\underset{I}{\Psi}$ for the given cloud. The determination of $\underset{I}{\Psi}$ for a given species under a variety of meteorological conditions is required as input for the model in Equation (2).

For certain species radar can follow individual insects up to 10 km, or so. From this radar data, $\underset{\rightarrow I}{\Psi}$ for individual insects can be determined. In addition, if two or more insects are being followed over the 0 to 10 km range, then information regarding the Lagrangian diffusion of insects can be determined.

If the insects are too small, too dense or too far away, radar can measure the changing shape of the insect cloud as it moves through the air. From these changing shapes, a measure of diffusion of the cloud can be determined. This measure is the Lagrangian form of $(\underset{\rightarrow}{K} + \underset{\rightarrow I}{K})$. By other meteorological means, the quantity $\underset{\rightarrow}{K}$ can be estimated. Hence, the Lagrangian form of $\underset{\rightarrow I}{K}$ can be determined for various meteorological

conditions. Through proper approximations, the Eulerian $\underset{\rightarrow}{\underline{K}}_I$ can be determined from the Lagrangian $\underset{\rightarrow}{\underline{K}}_I$.

MODELING vs RADAR·MEASUREMENTS FOR SPECIFIC EXPERIMENTS

Dropping Parasitic or Sterilized Insects from Airplanes

If radar is used to track the "flight" of an insect cloud dropped from an aircraft, the sinking rates of the dropped species can be determined. In addition, we can obtain some knowledge of $\underset{\rightarrow}{\underline{V}}_I$ and $\underset{\rightarrow}{\underline{K}}_I$ for the given species. One problem may be that the insects may not act naturally under these airplane drops. Hence, $\underset{\rightarrow}{\underline{V}}_I$ and $\underset{\rightarrow}{\underline{K}}_I$ may not be representative.

Deposition Studies of Insects on an Area of Vegetation Surrounded by A Desert

Assuming sufficient radar coverage, a cloud of naturally occurring insects can be tracked from the air down to a planted vegetation plot in a desert. From ground samples the species can be identified. Radar information can be used for verification of local models and to determine $\underset{\rightarrow}{\underline{V}}_I$, $\underset{\rightarrow}{\underline{K}}_I$, and sink information.

Long-Term Monitoring at a Point

Long-term radar monitoring at a point can contribute information for the following purposes:
- Boundary and initial conditions for local models of the area covered by the radar.
- For interesting insect clouds, we can run back trajectories to determine the sources of the insects.
- Determination of source strengths right above the canopy tops.
- Determine $\underset{\rightarrow}{\underline{V}}_I$ and $\underset{\rightarrow}{\underline{K}}_I$ for the species common to the area.

Mesoscale Radar Networks

A radar network over a mesoscale region will contribute information for verifying mesoscale models, determining $\underset{\rightarrow}{V}_I$ and $\underset{\rightarrow}{K}_I$, setting the conditions on the boundaries of models, determining initial conditions, and determining source and sink strengths.

Regional Radar Networks in the U.S.

Radar data can be used to verify local and regional models. If interesting insect clouds show up over one or more radar sites, back trajectories can be calculated to determine the insect source area. Radar data will also contribute to the knowledge of $\underset{\rightarrow}{K}_I$, $\underset{\rightarrow}{V}_I$, source and sink strengths, and boundary and initial conditions.

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I.3 Dispersion of Gypsy Moth Larvae in Complex Terrain

Objectives:

1. Quantify aerial densities of dispersing larvae over a large volume.
2. Look at vertical profiles of dispersing larvae.
3. Provide experimental evidence in support of known dispersal behavior (e.g., periodicity) and the atmospheric dispersion model.

Justification:

The atmospheric dispersion of gypsy moth larvae (first instar) is a completely passive process. Yet, it is the only natural mechanism available to the species to increase its range, because the adult female is flightless. Consequently, an understanding of this dispersion process is important to develop and implement meaningful pest management control strategies.

For many years the general belief has been held that larval transport is a long-range process (the order of several tens of kilometers). However, recent dispersion studies and the development of an atmospheric dispersion model have shown that larval dispersion is basically a short-range process (the order of hundreds of meters) in the absence of persistent updrafts. The model has been verified for this situation by a series of field tests conducted on flat terrain.

Nevertheless, field observations in hilly terrain show a preponderance of heavily infested areas at or near ridge tops. To treat this situation the larval dispersion model has been extended to incorporate terrain effects. The modified model predicts a significant extension in dispersal range where sustained updrafts exist as, for example, in the vicinity of these ridge tops.

Verification of the model predictions in complex terrain situations is necessary. But, this verification is difficult to achieve using classical ground-based sampling schemes. Not only must the traps be placed over a large area in difficult terrain, but the three-dimensional wind field over the same region must be measured. Ideally we would like to erect an array of samplers in some three-dimensional pattern (which involves aerial samplers) and complement the array with a series of meteorological sensors to define the three-dimensional wind field. Such an operation, if possible, would be very costly.

The first-instar larvae is about 2 mm in length, less than 0.5 mm in diameter, weighs about 1 mg, and is profusely covered with setae. For radar to be useful it must detect these larvae from very short ranges (canopy height) to several thousand meters.

Plan of Work:

The radar can be ground-based, vertically pointing, and located on the valley between two ridges in an area of known heavy infestation where large numbers of dispersing larvae

are guaranteed. Because larval dispersions usually takes place during the daylight hours in late April and early May when other airborne insects are not present in large numbers, interference from other species would not present a problem. However, other airborne debris might pose a problem and several aircraft to sample probable targets may be required at least during some portion of the dispersal period (about 2-3 weeks).

An alternate location for the radar would be an elevated site with the unit oriented to look down the axis of the valley. This operating position allows a definition of the dispersion patterns over a larger volume (although ground clutter may cause problems). Also, the very short-range detection requirement can be dropped in this instance. A scanning mode of operation is desirable to determine larval density as a function of cross-valley position.

In both cases above, a definition of the atmospheric circulation patterns in the vicinity of the ridge tops and over the valley are necessary. Such data can be provided by chaff releases at appropriate times and locations.

Of considerable interest, but of secondary importance to this particular study, is the correlation of air circulation patterns with the aerial densities of the dispersing larvae. If such a correlation is possible, then it may be possible to use dispersing larvae as tracers of local air currents. This is a much broader, more general application to the problem of defining atmospheric circulation patterns using insects and other airborne materials as naturally-occurring tracers.

I.4 The Dispersal Behavior of Adult Male Gypsy Moths

Objectives:
1. Detect male moth dispersal.
2. Study periodicity of flight behavior (i.e., is there a diurnal pattern and, if so, is it correlated with meteorological parameters such as temperature, relative humidity, or wind speed).
3. Determine in what direction the moths fly with respect to the wind direction prevailing at the time.
4. Determine other flight characteristics such as altitude.

Justification:
Many observations have been made of single adult male captures in pheromone-baited traps at long distances from known infestations. Do these captures indicate a low-level endemic population or have the males migrated from a distant source? Little information on adult male flight behavior above the canopy is available because there is no convenient way to continuously observe this region.

The adult gypsy moths emerge in late July. Observations of daytime male flight beneath the canopy have been made as well as observations of an early twilight flight to resting sites in the canopy. However, no observations of nighttime activity have been attempted. Also, above-canopy observations have never been made.

The results of this research may produce significant economic savings, as a result of redefining the need for control efforts. At the present time, in some localities, pheromone-trap lone-male captures in two or more successive years trigger costly and environmentally damaging spray operations. If we find that the males fly long distances accidentally, or undergo long-range transport brought about by meteorological events, a reevaluation of the significance of these captures would become necessary. To this end, another of the proposals set forth in this section addresses the problem of the "calibration" of pheromone traps and light traps in terms of relating the actual (aerial) populations to trap catches.

Plan of Work:
To achieve these objectives, we propose to use radar as the appropriate tool to monitor flight behavior of the male moths in the above-canopy region. The work of Greenbank and Schaefer with the spruce budworm clearly demonstrates the capability of radar to detect and monitor moths similar in size to the gypsy moth.

The study site should be located in an area of heavy gypsy moth infestation to maximize the number of adult males in the scan volume. In an area undergoing severe and extensive defoliation, the majority of moths in the air space over the canopy (as well as

beneath it) should be gypsy moths. Field verification of this point will be made.

A vertically pointing radar with the capability to detect these insects at extremely short ranges (just above canopy height) and out to several hundred meters must be used. If at all possible, it would be advantageous to analyze the return from single insects with respect to wing-beat frequency and/or body characteristics (perhaps by rotating the plane of polarization) to identify the signal as coming from a moth. If this is not possible, field verifications will be necessary; for this purpose, observing platforms and traps can be used. Supporting meteorological instrumentation to define prevailing weather will also be required.

I.5 Improving the Interpretation of Sampling Data from Aerial Trapping Techniques

Objectives:

To determine the relationship between aerial insect abundance near the canopy and the catch of commonly used sampling methods such as pheromone or black light traps.

Justification:

Aerial populations of insects are notoriously difficult to sample, consequently, there is a poor understanding of what happens to insects while they are airborne. The fields of insect behavior, population ecology, and applied pest management stand to gain from an improvement in our sampling capability. It is probable that we will rely on relative rather than absolute methods for most of our sampling in the foreseeable future, as relative methods are much more economical to use. However, the ability to convert relative measures to estimates of absolute density is highly desirable.

Once these relative measures have been related to absolute density, we can study the effects of the crop and meteorological conditions on the proportion of a population that is flying versus what remains at rest in the crop canopy. This would be especially useful for *Heliothis* spp. and similar species that scatter their eggs singly or in small clusters across a field. Knowing this proportion will allow an estimation of the total field population from a trap catch.

Plan of Work:

1. Select a number of fields (at least 2 or 3) of the major host of the insect that are in the phenological stage that is most attractive to the insect. To avoid identification problems, try to select fields where the insect of interest is the major insect present during experiments.
2. Monitor with radar from sunset to sunrise the space above the canopy (0 to 10 m) of at least 1 to 2 hectares of crop.
3. Determine the density distribution of moths within this area.
4. Sample populations with light traps, traps, pheromone traps, and other monitoring devices of interest.
5. Monitor environmental variables.
6. Sample the field population of eggs, larvae, etc.
7. Develop a model that will relate trap catch to absolute field populations as measured by radar.

I.6   Characterize the Meteorological Conditions and Systems That Annually Transport
      Cereal Aphids From the Southern Great Plains to the Northern Coast Plains

Objectives:
1.   Long Range: Develop a total pest suppression strategy that will give the greatest
      reduction in damage due to cereal aphids at the least cost and environmental hazard.
2.   Short Range: Elucidate through the use of radar the meteorological systems that move
      aphids vertically from low elevations to higher elevations; and, characterize the
      high speed movements that horizontally transport the aphids from overwintering areas
      in the south to the northern Great Plains.

Justification:
      Cereal aphids, such as the greenbug, overwinter near the Gulf Coast of Texas and
Mexico and are presumed to be transported over great distances to wheat fields in the
northern Great Plains. Damage from greenbugs to sorghum and wheat in Kansas, Nebraska,
and South Dakota is estimated to be $12 million annually. An additional loss of $750,000
is estimated for aphids on small grains in Minnesota and North Dakota. Effective popula-·
tion suppression strategies cannot be developed without an understanding of the movement
of aphids from overwintering areas.

Plan of Work:
      Through the use of appropriate radar techniques, monitor the vertical transportation
of aphids from grain fields during spring flights, and determine the probable transport
system for long distance movement.

I.7 Radar Observations of the Spatial Distribution of Insects Released from Aircraft

Objective:

Describe the evolving spatial distribution of insects, such as sterile pink bollworms, sterile fruit flies, and tachinid parasites when released from aircraft.

Justification:

Area-wide population suppression strategies often involve the release of insects from aircraft. Aircraft flight speed, altitude, and swath widths are set without a complete understanding of the effects of these factors, and the associated meteorological factors, on the distribution of the released insects. More efficient and efficacious release tactics need to be developed to reduce the overall costs of the population suppression programs using released insects.

Plan of Work:

At a fixed radar location, conduct observations of the dispersion of insects released from an aircraft. Such a program will include a parametric study of the effects of varying aircraft speed, altitude, and swath width. Environmental conditions play an important role in insect dispersion. The program should also include a variety of environmental conditions such as time of day or night, ambient temperature and local wind field. Various biological factors intrinsic to the insect will also be studied for their effects on flight duration and general behavior. Insects will be adapted to different biological phases to gain knowledge of ascending, transport, and descending phases of dispersal.

Another factor to be considered is the aircraft itself. Downstream turbulence generated by the aircraft will also affect the local dispersion of the released insects.

I.8 Long Distance Flight Dispersal and Migration Studies

Objectives:
    1. To determine the proportion of selected insects species that embark on "long distance" migratory flight following their emergence.
    2. To estimate the range of this flight.

Justification:
    The cabbage looper, corn earworm, and any other moths of economic importance can be expected (at least temporarily) to numerically dominate any other insects of comparable size, which will be flying in the same area.

    If successful, this study will provide the basis for determining mechanisms of dispersal (or migration) of the target species. The knowledge gained should result in new and better insect control strategies and improved crop management schemes. For example, local as opposed to regional control programs could be evaluated.

Applicability of Radar:
1. Short Range Studies
    Observations of flight down to crop level is required to monitor the proportion of moths in local "trivial flight." X-band radars currently used in entomological work have beamwidths (typically 1° to 2°) too wide to allow adequate low altitude (<50') coverage at their minimum workable ranges. For example, a radar with a 3dB beam width of 1.8° does not operate satisfactorily at elevations below 2.2° (when the first null in the beam pattern would be horizontal and ground returns from the main beam avoided.) The minimum workable range, allowing for receiver recovery and/or beam formation, would be 150 m. In addition, conventional marine displays are not designed to display trajectories in detail below 300 m range. Minimum altitude coverage is thus 20' - 40'; in most terrain more likely 50' - 60'.

    In consequence, very narrow beam millimetric radars or optical methods are required for detection near the ground.
2. Long Range Studies
    There is considerable evidence that certain diurnal insect species follow definite flight pathways in a manner similar to bird species. However, there is little information concerning nocturnal flight paths of pest species. Ground-based portable radars scanning possible routes such as rivers, mountain ridges, valleys, etc. are powerful tools for determining the extent of insect flyways. Initial species identification would be attempted via areal collection.

    X-band radars of the type already in use in entomological studies can detect individual moths of the size of the species mentioned at ranges of up to 2-3 km, and concen-

trations at much larger ranges. Individual ascending flight trajectories in the vicinity of the emergence zone would be accessible to the radar up to altitudes of 2000 m. The use of a second and third radar down the flight path would verify the continuation (or absence) of migratory flight up to several tens of kilometers. At longer ranges siting of the verification radars would be difficult unless the emergence zones were very extensive.

Plan of Work:
1. Team Composition
   a. Entomologist with 1 or 2 supporting staff.
   b. Radar scientist for analysis of radar data and planning.
   c. Radar technician with three assistants.
   d. Meteorological technician or scientist.
   e. Optical device scientist plus assistant.
2. Operational Plan
   a. Entomologist team identify suitably concentrated emergence zone (more than 5 larvae per m^2).
   b. Team deploys prior to expected emergency, meteorological measurements commence.
   c. Entomologists monitor approach of emergence period.
   d. Radar and optical device monitor background flight activity.
   e. Emergency rate studied by optical methods and visual technique.
   f. Development of flight followed by radar and optical device estimates of densities and trajectory distribution. Radars (2 or 3) maneuver, if necessary, into flight path downstream of source.
   g. Conclusions reported.

I.9 Use of Radar to Detect and Describe Insect Movement Across the Florida Peninsula

Objectives:

To determine if meteorological phenomena exist that explain the long-range movement of insect pests from or through peninsular Florida.

Justification:

Several major economic species of insects are assumed to overwinter in south Florida, Mexico, Central America, or the Caribbean Islands. Movement of these pests northward is not clearly understood; therefore, control strategies cannot be well developed.

Studies in North Africa, Canada, and Australia reveal that insect movement is closely related to meteorological phenomena. Detection of insects in the atmosphere may be accomplished with existing radar equipment, and thereby reveal concentrations of insects whose movement correlates with weather conditions such as fronts or inversions.

Peninsular Florida is considered the focus of development or the conduit of passage for several economic species of Lepidoptera. The acquisition of data that describe the general movement of insects across this area may make it possible to explain and predict the movement of these pests.

Plan of Work:

Two or three radar units with accompanying meteorological capability and air sampling capability can determine in a 2 to 3 year period the general nature of insect movements up and down the peninsula. Once these movements are known they can be coupled with existing or developing knowledge of the population dynamics and behavior of specific pests. Additionally, radar facilities at various military facilities about the State may also be used. These facilities are largely along the coasts and would be useful in detecting migration across the Gulf or Florida Bay. Other radar detection units might be located on ships, oil drilling platforms, or islands in the Caribbean area.

Logically, research emphasis would move from the development of general information to the application of radar to studies of the behavior and movement of certain pest species. If the migration of key pests from Florida can be established, then studies should be expanded into the regions that receive these pests.

While this proposal emphasizes the application of radar as a detection and sampling tool, it can only be used effectively in an environment of balanced research developing basic behavioral and population information.

I.10 Development of Information·Describing the General Movement of Insects·Across the Southern United States

Objective:

   To determine the direction, magnitude, and timing of long-range movement of insects across the southern United States.

Justification:

   Movement of pest insects over long distances has·been determined to occur in various areas of the world. Such movement has never been adequately documented in the United States in·terms of timing, direction, and numbers of migrants. If the long-range migration of certain key insects were known, control strategies could be devised to reduce or eliminate them at their source, or to predict and intercept their movement.

Plan of Work:

   Establish a network of about 10 simple radar stations at about 200 mile intervals along an east/west transect from the Georgia-South Carolina coast to South Central Texas. Each station would consist of a fixed radar unit·that could monitor insects passing directly overhead in several vertical zones of elevation up to 2000 m. Information obtained would consist of density profiles, and rate and direction of movement. · Concurrent detailed meteorological information would·be obtained. The units would operate 24 hours each day for a period of 2 to 3 years with the sampling rate within that period to be determined by local flow rates. Air sampling capability would be established to verify radar data and to correlate radar data with particular.types of species of insect.

   These data will be used to develop a general description of insect movement across the southern United States in relation to weather and agriculture. In addition·, this information will establish the possible annual migration routes of key pest species.

II. PEST MANAGEMENT

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INTRODUCTION

There are many examples of long and short-distance dispersal of economic insect pests and beneficial species from cool-season host reservoirs and/or overwintering sites. In addition, significant dispersal of these species often occurs during crop and animal production seasons. Integrated pest management concepts highlight the importance of understanding and determining the causes and effects of insect dispersal, as well as manipulating it to advantage in management systems. Pest management focuses on applying control pressure to the entire or large portion of the total target insect population. Insects do not recognize country, state or county political boundaries; so, the influence of dispersing arthropod populations into and out of crop and animal production areas has to be considered as an integral part of the pest management system.

STATE-OF-THE-ART

Evidence of insect migration comes from various sources: (a) direct observations of large numbers of insects flying steadily in a definite direction, (b) sudden appearance of winged insects in an area where no previous local breeding or emergence is known, (c) the presence of insects over lakes and far from land over the ocean, or in snow at high altitudes, (d) insects that occur only during certain seasons and are not found in any stages at other times of the year, and (e) release and capture methodology.

Data obtained using these techniques are limited in that records are at ground level at the point of arrival or departure and represent a small sample of the total area. Although visual observation of directed flight may be seen during the dispersal period, there is a dearth of information during the airborne phases of insect dispersal. Limited studies were conducted as early as 1936. Using airplane sampling techniques at levels of 6 to 500 meters it was demonstrated that a large number of insect species were present in abundance at high altitudes. More recently, blacklight traps on a television tower caught corn earworm moths above 300 meters. These studies highlight the economic importance of airborne insect dispersal as related to the spread of pest infestations.

Our lack of adequate sampling techniques limits both the determination of factors that affect migration, and the study of insects during their airborne dispersal phase. The economic importance of arthropods in agricultural production systems, and the opportunities to define dispersal for the purpose of developing and manipulating control strategy, are sufficient justifications for the development of appropriate remote sensing technology to study dispersal.

Radar technology has been effectively used to study migration of several economic insects including spruce budworm, several locust, and grasshopper species. Application of radar technology as a research tool to corroborate dispersal of other major insect pests appears to be a feasible initial approach to the study of the flight characteristics, distribution, and spread of these pests from overwintering areas and/or within and between crops.

Meteorological information is also essential to define the role of weather and air movement in contributing to or regulating insect dispersal.

We recognize that the initial use of radar will be as a research tool to help define the flight activity of the selected pest-species of interest, and to help correlate such activity with basic biological and meteorological parameters. Until such studies have been completed, and the radar capabilities understood, it is difficult to envisage how radar can be used in a pest management program. At present it is only possible to examine some of the information that a pest manager requires, and which, subject to the outcome of the research phase, radar can provide. We also recognize that before the impact of radar on pest management schemes can be assessed the schemes themselves must be defined; this in itself requires significant effort.

Examples of several important insect species that may be considered appropriate for migration and dispersal studies are as follows:

The Pink Bollworm. The Pink Bollworm was first found in Texas in 1917. By 1967 the pest had become established in all cotton producing areas west of Louisiana and Arkansas except the San Joaquin Valley of California. It has reached economically damaging levels requiring control procedures in California and Arizona each year since 1965. Repeated insecticide applications to control this pest resulted in resistance and secondary pest outbreaks. Losses in California and Arizona in 1977 were estimated to ca. 135 million dollars. In addition, migrating pink bollworm moths threaten to establish the insect in the one-billion-dollar cotton-production areas of northern California.

The Fall Armyworm. The fall armyworm causes direct loss of $150 to 200 million per year in the Southeastern and Atlantic Coast States. Losses and control costs for sweet corn in Florida alone are more than $15 million per year. The development of a double-cropping system with corn and sorghum in the Southeastern United States cannot be developed without fall armyworm control. This restricts the development of the cattle industry in the Southeastern States since feed and grain deficits exceed 10^{10} kgm per year. Planting

200

dates of corn in the Southeastern and Atlantic Coast States are dictated by the fall armyworm.

This insect only overwinters in southern Florida, Louisiana, and Texas; thus, control measures applied during winter and early spring could eliminate the need for control measures applied outside of the overwintering area. Migration occurs each year north to Georgia and extends northward into Canada. A fall armyworm population management system based on ecology, behavior and migration patterns could increase agricultural production, reduce pesticide use, and decrease the loss of millions of dollars.

Heliothis (corn earworms and tobacco budworms) overwinter as diapausing pupae throughout the Southern U.S. (south of 45°N) and as continuous generations in southern Florida and Texas, and certain western states. Active spring and summer generations migrate to agronomic crops such as corn, soybeans, sweet corn, sorghum, cotton, peanuts, tomatoes, lettuce, and cabbage. The estimated losses due to attack of *Heliothis* to these crops, including the cost of chemical control, is $1.2 billion. Present control strategies use chemical and other control methods after economic populations are already present. This results in continuous decision-making and control expense throughout the wide potential range (most of U.S.) of these insects. An ecologically based, environmentally sound control strategy is needed to prevent the initial development and spread of economically damaging pest populations. This control strategy must include an understanding of the factors that influence both short and long distance movements of *Heliothis* as well as characteristics of these movements.

Currently used monitoring methods in pest management systems for these insects involve trapping for detection of adult insects, as well as tedious, time consuming, and highly variable plant sampling methods to detect other stages of the insect. The need for control action is based on these data and information obtained on crop growth characteristics and economic thresholds of the target species. This occurs in many cases after the infestation has reached damaging levels.

Radar observations might determine size estimates, temporal relationships, and dispersal distributions of mobile adult populations of *Heliothis* in relatively small-area (local grower, county) pest management programs. Such observations would be used to provide an alert system for possible infestations. Intensified local field sampling could result in judicious timing and application of chemical control measures on the basis of need. This would reduce greatly pesticide use, increase effectiveness of control measures, and reduce crop damage and loss.

In the case of insects such as fall armyworm and *Heliothis* spp., and possibly many other insects that overwinter and/or continuously breed in restricted southern areas, the possibility of applying suppression methods to the total population in those areas appears a promising pest management approach. If achieved the migratory populations which result in initiation of infestations over hundreds of square miles involving many states might be

significantly reduced.

Radar technology to verify and characterize these migrations in terms of numbers of insects, time of occurrence, distribution and length of flight as well as airborne behavior could provide the basic information essential to assessing the feasibility of such a total population pest management approach.

DEVELOPMENT STRATEGY AND RECOMMENDATIONS

1.   Determine capability of existing radar technology to operationally identify and track mobile pests such as fall armyworm, pink-bollworm, *Heliothis* spp, and other major pests.

2.   Characterize and study the distribution and movement of the above pests; and conduct studies to compare the efficiency of radar systems for monitoring populations with other insect monitoring systems in pest management programs. Radar technology may prove to be more cost effective for obtaining this information. It may also provide further data of operational use, whose value only become apparent during the research phase.

3.   Determine the role of weather fronts in the movement, dispersal, and distribution of mobile pests, and incorporate such relationships in operational pest management systems.

4.   Relate damage potential of mobile insect populations to radar observed indices within and between crop systems.

5.   Develop radar technology to provide information which is of use in making pest management control decisions. Such information should include, but not be limited to, time of occurrence, numbers, distribution, and further displacement of key insect pests. For example, if radar capability indicates potential as an early warning monitoring system for key pests in corn, cotton, soybeans (fall armyworm, velvet bean caterpillar, loopers, *Heliothis*), and other field crops, an appropriate decrease in lead time for preparedness for applying control strategies could dramatically increase effectiveness and reduce damage and crop loss.

6.   Industry, university, and Federal programs should include basic radar entomology and meteorology research, and their applications to operational pest management programs. In addition, mechanisms should be included to allow transfer of information between all phases of the programs.

7.   A developmental activity to assess the likely impact of radar on existing pest management procedures would help put the potential operational use of radar into perspective.

8.   Radar may provide, in addition to more data for existing pest management systems, information useful in formulating new concepts and practices in pest management; serious

and continuing study should be given to this providence.

9.   On the basis of current knowledge and experience elsewhere with the use of radar in pest management, at least three qualitatively different strategies using radar can be envisaged as potentially useful in operational programs:

(a)   Local surveillance - using a single sophisticated radar (mobile or static) to monitor local pest activities.

(b)   Regional Surveillance - using a network of simple inexpensive radars (or microwave devices) to monitor pest activities over a region.   Individual "point" measurements can also be correlated with traditional pest activity observations on a larger scale.

(c)   Airborne radar - to provide information over distance scales that cannot be achieved by ground based systems.

III. RADAR TECHNOLOGY

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INTRODUCTION

This group report presents a basic plan to determine the extent to which radars can be used for resolving entomological problems. There is ample demonstration in the literature that certain radars can provide information of value to entomological research and pest management. For example, radar has been used with success to detect the movement of such insects as locust (Africa) and spruce budworm (Canada) with respect to biomass and vertical distribution. However, there has been no dedicated effort to develop new or adapt existing radar technology for use against insect pests such as the screwworm (animals), bollworm (crops), and mosquitoes (humans), which are of major importance to the United States.

A preliminary approach to the entomological use of radar must recognize that we know little about the geography of insect migration and dispersal. In contrast, the routes and timing of migration of many bird species had been inferred from banding studies when radar was first proposed as a tool for the study of bird migration. In addition, birds had been regularly detected by military radars and identified as a source of interference (clutter) with the intended target. Hence ornithologists could choose to observe at selected fixed site radars and expect results. Not so with entomologists and insect observations. To insure that collected data are meaningful, the radar system must be properly positioned in an area where ground data exist, or can be easily obtained, on insects; and, preliminary studies must concentrate on accumulating data from numerous areas where experience and insight indicate insect migratory paths may exist.

The radar should also be as simple as possible for the job. Ornithologists didn't have to worry about radar simplicity. At a large fixed-site installation, a full crew of personnel is permanently assigned to the radar operation and maintenance. Although costing methods have changed at government installations in recent years, the critical years for radar ornithology, when observing techniques were developed and confidence was obtained that useful observations could be made, were conducted at no cost to the ornithologist during slack periods of normal radar use. Hence radar complexity was irrelevant

to the ornithologist's thinking. As stated in the last paragraph, such will not be the case for insect observations. The radar and crew will have to go into the field, at night, and at some distance from the normal work station of the personnel. Since field programs are costly, especially if highly complex systems are required, we emphasize:

KEEP THE INITIAL RADAR SIMPLE AND PORTABLE.

We also considered the merits of an airborne system versus those of a ground based system. There are two aspects to this problem depending on whether the radar is to track a single insect locally or swarms along possible migration routes. The choice of airborne as opposed to multiple ground radar will depend on which objective one has in mind.

For the tracking of a single insect a ground-based radar is to be preferred since the insect will probably be a reared or tagged individual and will be released near a fixed site from the ground. Since the insect will fly into the sky the radar will track above the ground clutter. On the other hand, an airborne radar will have to look down at the ground and the insect might be lost in the background clutter. An aircraft is preferred when tracking targets over long distances is desired. It is not likely that airborne radar will be able to track single insects, but it might be capable of tracking swarms. Thus airborne radar might prove of value for covering long range flights of insects.

Alternatively, a number of small portable ground radars might be positioned in areas where entomologists believe migration routes exist. The success of this depends on how well migration routes can be predicted. This technique would probably have less range capability than an airborne radar because of the large number of radars that would be required.

We propose that an orderly investigation be undertaken that will clearly show the capabilities as well as the limitations of radar in contributing to the solution of entomological problems. By orderly investigation we mean that applications of simple radars be considered first, followed by more elaborate radars with greater capability but with greater attendent cost. Ultimately an airborne system might be needed; this is included in our plan. The proposed plan consists of five tasks that should be executed with an initial priority according to the order of listing.

Following the five tasks are ten conclusions and recommendations that should be used to guide the future development of radar entomology.

III.1 Exploratory Research

Objective:

    To determine the characteristics of the backscattered energy from insects at radar wavelengths, and to determine the entomological information that different radar systems can extract from this energy. The study of radar system capabilities will emphasize simple systems and approaches that produce achievable and practical applications that maximize the benefit - cost potential of radar use.

Justification:

    The design of field programs in entomology and pest management that use existing radar, and the optimum design of new radar systems for such programs, depend strongly on understanding the capabilities and limitations of radar for insect research. The target (insect) scattering characteristics and their temporal behavior contain most of the basic information necessary for such understanding.

    Additional information must be obtained about the behavioral characteristics of groups of insects. The extent of insect aggregative behavior (relative to a radar pulse volume), the altitude of mass flight, and other mass dispersal features are necessary adjuncts to information input to effective radar design.

    Since we lack adequate knowledge of insect behavioral and electromagnetic scattering characteristics necessary for optimum radar design, an orderly development of radar entomology should start by exploring the capabilities of low level radar technology. This approach will be the most cost effective since it will allow important informational feedback to the development of future radar systems, and it will give entomologists the relatively low cost experience with radar that is necessary for the development of sophisticated programs.

Plan of Work:

    A detailed measurement program on free flying single insects will be conducted with radars using wavelengths from the millimeter through mid-centimeter region. Measurements will include the following:

    1. Radar cross-section measurements of selected insects in free flight and on model ranges should be made as a function of aspect angle to characterize the three dimensional nature of insect reflectivity in flight. Probability distributions of cross-section should also be determined and at all radar frequencies of interest. These data will be useful to modelers who must infer flight characteristics from rudimentary radar observations. More important, these measurements will establish boundaries for radar decisions pertaining to system dynamic range, power required, antenna gain, and other system specifications.

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2.   Doppler frequencies and echo signal amplitude modulations produced by wing-beating and other internal motions of the insect should be carefully measured. These data will serve the analyst who may attempt to develop a discrimination technique for the identification of an insect's family, genus, or species. These data will also assist the radar designer in determining the Doppler bandwidth characteristics for development of MTI or certain other (adverse) environmental rejection systems.

3.   The measurement of the polarization characteristics of selected insects will allow the analyst to determine whether polarization processing should be an integral part of the measurement radar. A determination of the desirability of including polarization processing early in the design considerations will save expense and modification, should polarization prove to be a valuable discrimination technique. Measurements should be made with two orthogonal polarizations (such as horizontal and vertical) and the cross-polarized component. In particular, the potential use of polarization measurements to provide the aspect ratio of the insect should be determined.

In addition to measurements on single insects, investigations that concentrate on specific entomological problems as outlined in the other session reports and that make use of a radar's primary and most elemental capability (which is the ability to provide volumetric monitoring and surveillance of insect dispersal and behavior with time) should start early in any long-range program. Such studies will include correlation of meteorological parameters with the time, rate, direction and distribution of insect movements in both the vertical and horizontal planes. Studies such as these can be handled without the use of sophisticated, high-level radar technology. Existing off-the-shelf radar systems can provide immediate and achievable results in selected, practical applications. In such cases program costs are minimized with high probability of success.

III.2 Optimum Radar Design

Objective:

1.) To establish the optimum requirements for wavelength, power, beamwidth, polarization, coherence, noise figure, pulse rates, pulse lengths, receiver types, dynamic range, and signal processing and display of a ground-based radar to fulfill a specific mission. The mission must be defined in terms of numbers of insects to be detected, insect identification requirements, minimum and maximum detection range, and biological information desired.

2) To specify a dedicated radar, or radars, tailored to the general needs of entomological research and pest managemer

Justification:

Presently existing, or partially modified, radar systems are not anticipated to be optimally suited to the purposes of entomology or pest management, nor is it expected that one system will be optimal for all entomological uses. The special requirements of entomology, which include short to long range detection and tracking of targets with very small radar cross-sections, spatial density mapping of targets, target identification, low system cost, ease of operation and maintenance, etc., clearly dictate that a system study be conducted to determine the trade-offs between various parameters of the radar.

Plan of Work:

A system study must be done to determine how well radar can satisfy specific entomological measurement needs. Two examples of radar measurements to be examined are:

1. The sampling of insects that pass over a radar site using a vertically pointing radar. The vertical distribution is determined by measuring insect densities at various altitudes, the direction of insect flight from orthogonal polarization measurements, wingbeat frequencies from spectral analysis, and insect size from reflectivity.

2. The rapid determination of three dimensional coordinates of insects in a large air volume using survey radars. The radar must be capable of searching in various modes such as sector scanning, helical scanning, fixed elevation scanning, and range-height scanning. Two categories can be considered: (1) Short-range radars with 1 to 5 kms maximum range for single insects, and (2) Long-range radars with 5 to 50 kms maximum range for single insects.

Other programs that need including are described in the Entomological Research, and Pest Management Group reports. More specific inputs to the study will come from the results of the Exploratory Research task previously defined. Of crucial importance to successful completion of this task is a detailed characterization of the dynamic radar cross-section of expected targets, the potential target position with respect to clutter,

and the data rates and display requirements for field operations. Also, MTI (Doppler processing) and the need for pulse compression should be considered, as well as the potential of radars using millimeter and laser wavelengths.

III.3 Tracking of Individual Insects

Objective:

To determine the full potential of radar for the tracking of free flying insects that are either randomly acquired or experimentally manipulated and released.

Justification:

Many significant entomological studies and pest management programs can be developed if the flight behavior of insects can be observed over relatively long distances and subsequently correlated with other behavioral and physical conditions. Several possible experiments using data obtained from tracking of selected individuals include: comparing the dispersal and flight behavior of laboratory-reared insects with native insects by releasing reared insects in a natural environment; correlating the time, place and behavioral activity of an insect at the beginning of dispersal or migration with environmental conditions; and, assisting with the determination of the flight origin and goal of single insects flying over a radar site.

Dark or light adaptation techniques can be used to put an insect in a nocturnal or diurnal stage of flight activity. Such a possibility allows releases during low flight activity of other insects and, hence, minimizes the problem of confusion with other insects during tracking.

Plan of Work:

Radar capabilities, complexity, and cost are, as in any of the other proposed programs, critically dependent on the insect to be observed, its placement relative to clutter, and the required precision of results. Existing tracking radars should be used first to delimit present system capabilities. Entomology results obtained from tracking in the 0.1 km to 10 km range should be emphasized, with primary consideration to projects where insects will be flying at least several degrees above the horizon. Aircraft or balloon released insects should be considered first, because many target characteristics (physiological state, species identification, physical parameters, etc.) can be determined and potentially controlled.

A parallel program should be conducted that develops insect tagging techniques using diodes or other devices to modify the returned signal in some unique way. Tagging the insects with a metallic material could enhance the radar cross-section and make the tagged insect more distinguishable from other insects in the immediate volume. Single untagged insects have been successfully tracked; results of radar tracking of metallic tagging are not available.

The use of a diode tag that produces harmonics of the fundamental transmitted frequency, or the use of any other device that could modify the transmitted signal in some

unique manner, has two immediate advantages: (1) the clutter problem is eliminated since. there is no return of the modified signal from any object except the tag, and (2) stationary insects close to the ground could be located. The technology for a harmonic radar unit is available, and a radar unit using the second harmonic from a diode tag is currently being developed. It appears that this type of radar will have a relatively short range of 100 meters or less unless more efficient tags are found.

Laser radars have the capability of providing much higher resolutions than microwave radars. A laser insect-tracking radar would be able to track an individual insect in regions of higher insect density, and closer to the ground than can conventional radar. The technology for a laser radar appears to be available, but it would require the development of a dedicated instrument.

III.4 Airborne Radar for Insect Detection

Objective:

To develop airborne radar techniques for monitoring insect densities over large regions.

Justification:

The operational aspects of pest management encompass vast regions - often covering millions of square kilometers. Coordinated regional management will require insect detection and dispersal monitoring in a relatively short time period throughout the region. At present it is unrealistic to expect that a large regional network of ground based radars will be established to do this monitoring. A single airborne system could provide the regional coverage assuming the appropriate data can be obtained.

Plan of Work:

There have already been insect observations obtained with a nadir pointing range gated system that eliminated ground clutter. Initial studies should more fully explore the potential of this approach. The next degree of complication is to extend the swath covered by a downward looking radar. This may be accomplished by scanning a pencil beam in a plane perpendicular to the heading of the aircraft. Alternatively, the pencil beam can be scanned in a conical pattern about the vertical axis. A low-flying aircraft with a high-powered radar scanning a pencil beam about the horizon might be able to detect high-flying insects if the curvature of the earth masks the ground echo. The design of such a radar should be considered since this might be the only method available for detection at long range.

A program using an aircraft mounted radar may be more expensive than a groundbased program due to increased logistical and operational complexities. However, airborne radar is advantageous for covering large areas and for following the movement of insects over long distances. Plans for learning what airborne radar can, and cannot, do should be initiated early. Aircraft includes light and heavy fixed wing aircraft, as well as helicopters. The use of radar in a tethered and high altitude fixed location balloon might also be included in the proposed study.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations were reached by the Radar Group regarding the use of radar for the solution of entomological problems. They are listed in order of priority.

1. The initial efforts using radar as a new tool to study insect flight activity should be undertaken at 3-4 locations under differing climatic conditions. The insects selected should be species that affect crops, animals, or man. The climatic conditions should include those of the west coast, Midwest and Southeast regions of the United States. Consideration should be given to locating these initial efforts at sites where multidisciplinary research staffs are available.

2. Initially, radar should be used for only a clear, well-defined problem involving an insect species-complex. Examples include, tobacco budworm, corn earworm, grasshoppers, or mosquitoes.

3. An example of a simple measurement for which radar should be used more widely is the determination of the vertical distribution of insects. This can be accomplished with an upward-looking radar. The relative density as a function of height can be obtained. However, if the radar has sufficient range resolution and if the density of insects is sparse, an absolute count per unit height might be possible.

4. In planning and executing experiments with radar, adequate resources should be provided for the recording, processing, and display of radar data. The proper handling of radar data is important to the success of any experiment; it must be included from the very beginning.

5. A systems-oriented study is recommended to determine the optimum configuration, or configurations, of a ground-based radar designed to meet the needs of entomology and pest management. The study should include such factors as the choice of wavelength, dynamic range, polarization, type and size of antenna, optimum power, and any parameters that enter into design trade-offs. MTI (Doppler processing), need for pulse comparison, millimeter waves, and laser radar should be included.

6. Special attention should be given to the displays to be used with insect radars and to the interface of the display with the experimenter. Radars used for insect research should include a range-height indicator (RHI) that provides a cut through the vertical plane at some azimuth, as well as the normal plan-position indicator (PPI) and A-scope (amplitude vs. range).

7. Flexibility should be designed into the radar so that the experimenter can interact with the radar and adjust the parameters according to the needs of the experiment as it progresses. The parameters that are potential candidates for flexible, interactive operation include the direction of antenna pointing, spatial scanning mode, choice of data

displayed, polarization, pulse width, and a choice of linear, logarithmic, or Doppler (coherent) receiver.

8. A study should be made of the possible methods for using radar in an aircraft. Particular attention should be given to the type of antenna scan to be employed and the means for avoiding ground clutter. Designs of radars for possible use in light and heavy fixed-wing aircraft and helicopters should be made. The possible use of tethered and high altitude stationary balloons should be considered. The trade-offs between an airborne platform and multiple ground-based radars, both fixed and mobile, should be a part of this study.

9. Observations should be conducted to determine the total information about insects that can be extracted from a radar signal. Both single insects and swarms in free flight should be observed to determine:

    a.   The temporal fluctuations of the backscattered energy (echo amplitude) to obtain the probability distribution of target cross-section, power spectra (over short and long time intervals), and amplitude signatures,

    b.   polarization power scattering-matrix elements,

    c.   Doppler signatures.

Simultaneous measurements of position versus time should be acquired, along with optical data when possible, to analyze the various data products in terms of the behavior and physical characteristics of the insect.

10. A design study should be made of the type of radar best used for the tracking of individual insects. Means for tagging selected insects with devices that modify transmitted signal should be considered. Laser radar should be included as a possible candidate because of its potential for high resolution.

IV. FIELD PROGRAM DEVELOPMENT

Participants: R. Rainey, Chairman

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INTRODUCTION

While radar can provide unique and valuable new information anywhere that pest insects appear in numbers in flight, the group considered that it would be most useful to concentrate on one specific problem: the winter control of particular major pests, in their restricted overwintering areas in the southern United States, for the protection of next summer's crops over much wider areas farther north.

This concept of strategic control (undertaken in the interests of, but outside of, areas threatened by subsequent attack) poses the crucial questions of where and when to undertake such operations; it also highlights the fundamental need, stressed by Dr. Knipling, to locate and assess the whole of the pest population involved - and these are all questions to which radar is uniquely able to help in answering. The group report separates considerations of the biological problem, relevant radar technology, and meteorological support.

Program cost estimates were not considered. However, an appendix to this report gives details of equipment and staffing of actual radar field studies of the spruce budworm in New Brunswick, Canada.

THE PROBLEM

Several species of Lepidoptera result in a combined economic loss in the order of $500 million annually to agricultural products in the Southeast and eastern United States. These particular Lepidoptera are characterized by not having developed mechanisms for surviving cold temperatures in the northern part of North America; they must rely on continuous generations in the extreme southern portions of the United States (and sometimes farther south) to maintain the species. The fall armyworm, cabbage looper, soybean looper, beet armyworm, and velvet bean caterpillar are the most important of Lepidoptera possessing this common attribute; the group agreed that initially these species need to be considered together, as elements of a single, complex problem, not least because of

probable difficulties of recognizing the radar-echoes of individual species. The corn earworm and tobacco hornworm also complete continuous generations in this area, but they also diapause as pupae in the soil up to 45°N.

The total area involved or suitable for continuous generations of these species in the Southeast is limited by cold temperatures with the average boundary believed to be located from mid to north Florida.

The losses due to control costs plus actual crop loss are only the direct losses and do not take into consideration their impact on the total economy of the region. For example, the cost necessary to control the fall armyworm is the major factor limiting cattle production in the Southeast, because it prevents the economic production of double-cropped feed grains necessary for a more intensive cattle industry.

The density of these populations in their overwintering area, and the process of dispersal throughout the Southeast and eastern United States, are not known nor have they been researched in a systematic manner. Pest managers anticipate that, if this adequate biological and ecological information becomes available, it might be possible to identify specific areas of high populations requiring treatment, and so to develop and implement suppressive measures to reduce populations sufficiently in their overwintering refuges, therefore preventing economic losses throughout the Southeast and eastern United States later in the season.

The greatly restricted overwintering area for the fall armyworm, cabbage looper, and several other important agricultural pests thus offers the possibility of achieving their effective strategic control in an area that may be less than 10 percent of the agricultural region to which they spread in highly damaging numbers and where control efforts are necessary during the summer crop growing season. The purpose of suppressive efforts in the restricted overwintering area would be to reduce the migrating populations to such low levels that they will not have time to increase to highly damaging levels before cold weather again decrease the populations and restricts distribution. Before an assessment can be made, however, of the feasibility of this regional approach to effective management of a pest like the fall armyworm, as well as other species, it will be necessary to have more quantitative information about the behavior, ecology, and dynamics of the pest in the overwintering areas than is now available. It will also be necessary to determine if the population existing above the overwintering area in the spring and summer originates primarily from Florida or whether substantial direct migration occurs from Cuba or other islands in the Caribbean area, and/or from the mainland of central or South America. Therefore, developing information on significant long range movements of the insect into the southern United States will be one of the important aspects of the overall research program.

To achieve a high degree of suppression in the overwintering area and thereby cause a proportionate reduction in the initial migration population, it will be necessary to

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identify the various habitats within the overwintering area where reproduction is occurring. The fall armyworm, for example, is known to feed on a number of cultivated and wild host plants. For control in the larval stage, it will be important to determine the amount and distribution of host plants that contribute to the total population, and to estimate the proportion of the total population due to the various host plant types with a considerable degree of accuracy.

Several methods of suppression will likely have to be used and appropriately integrated in order to achieve a high degree of suppression at minimal costs. For example, in habitats having low moth densities the release of sterile males may be the most effective and practical procedure to employ. In habitats having moderate densities the release of mass produced biological control agents may be an effective and acceptable procedure. In habitats having high densities, such as sweet corn and highly favorable Bermuda grass pastures, it may be necessary to apply chemicals or biological insecticides.

Information on the time and extent of movement of moths originating from one breeding area to other breeding areas may be highly important. Do moths tend to disperse in low numbers into large potential breeding areas, or will they tend to concentrate in relatively restricted but highly favorable breeding areas such as sweet corn fields, vigorously growing Bermuda grass pastures, or favorable wild host plant habitats? The rate and extent of movement, and particularly of possible concentrations of moths in relation to convergent wind-systems and other meteorological factors, must be monitored and the data critically analyzed.

Information on the movement of moths and the detection of areas of larval development will require the co-ordinated and greatly intensified use of all available survey and population assessment techniques and reporting systems, including radar equipment, aircraft with special insect collecting devices, sex pheromone traps, and visual surveys to determine where larval infestations occur. The development of chemical assay methods that would identify the origin of moths, both to host plant types and to habitat types, would be very useful as a guide for maximum suppression efforts.

Careful analysis of data obtained by the various survey systems will be necessary to obtain an overview of the sources, behavior, and dynamics of the overwintering moth populations. Studies to determine when significant moth migration from overwintering areas to nonoverwintering areas begins each season, and the extent and rapidity of such movement, will be one of the most important aspects of the overall study. The movement information should be of such nature that reasonably good estimates can be made of the actual numbers of moths, and the proportion of the total overwintered population, that disperses from overwintering to nonoverwintering areas.

RADAR CONSIDERATIONS

Radar can monitor population levels of insects in flight and track some migratory species of insects, and has already proved a powerful tool to use to improve understanding of the dispersal habits of other pest Lepidoptera; a thorough understanding of dispersal has been found essential to the development of improved pest management systems for these species.

Ground-based radar has demonstrated regular night flight of a number of important insect pests in numbers and at heights previously entirely unsuspected, and in favorable circumstances (Schaefer, 1976) has been able to recognize echoes from a particular species (and even sex) of locust and grasshopper. Airborne radar has provided continuous height-density profiles of pest Lepidoptera in flight up to many hundreds of meters, along traverses totalling many thousands of kilometers, over an area substantially larger than the overwintering area of fall armyworm in Florida, and with a vertical and horizontal resolution of a few tens of meters.

There are four systems of radar operation useful to this project. They are:

1.   Short and moderate range ground-based radars, which are procurable at low cost and illustrated respectively by man-portable military surveillance sets, considered in detail below, and by the USDA installation at Phoenix described by Wayne Wolf (p. 159).

2.   Shared time at existing fixed installations.

3.   Airborne vertical sounding radar: such as the one used by Schaefer in the Canadian studies of the spruce budworm moth.

4.   Airborne laser-radar (lidar) and scatterometer systems such as those being developed at the NASA Wallops Flight Center.

The Use of Small Surveillance K -band (16 GHz) Radars in Monitoring the Emergence of Fall Armyworm and Cabbage Looper Sized Insects

The cabbage looper moth has a radar cross-section of about $2 \times 10^{-5} m^2$ at 16 GHz.[*] The fall armyworm moth is also about this size. A relatively inexpensive U.S. Army man-portable radar operates at 16 GHz and has the following nominal characteristics: horizontal beamwidth is on the order of 1.3° (24 mil) and vertical beamwidth of about 2.7°

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[*] S. B. Adler and R. S. Johnson, 1962. "New Backscattering Computation and Tables for Dielectric and Metal Spheres," Applied Optics, pp. 655-660.

(48 mil).[*] It has a range increment or "range bin" of 30 meters. It will reliably detect a man ($\leq$ one square meter) at 5 kilometers so that, using the inverse R^4 scaling law, it will detect a $2 \times 10^{-5} m^2$ cabbage looper sized moth at 333 meters.[**] This radar can scan over sectors up to 90° azimuth.

Insect pupae densities as great as $300/m^2$ ($30/ft^2$) exist in improved Bermuda grass pastures. Furthermore these animals can be expected to emerge during approximate 2 hour periods over five successive days (10 hours total) and to fly off down-wind at a ground-speed of the order of 10 km/hr. Treating these factors linearly - the 300 insects will occupy a volume of 1.0 m^2 x 10 km/hr x 10 hr so that the average density is $300/10^5 m^3$ or 1 insect per 333 m^3 of air space. We calculate the radar resolution cell at this 333 m "1 insect range" as $\pi/4$ x $\frac{24}{1000}$ x 333 m x $\frac{48}{1000}$ x 333 m x 30 m $\approx$ 3000 m^3. In the intense "swarming" described, this volume would contain 3000/333 = 9 insects. This filling of the resolution cell with 9 objects allows further beam filling target approximations. The return for a beam-filling target (unlike a point target) falls off inversely as the square of the range so that a return of 9 times minimum corresponds to an increase of range to 9 = 3 times minimum range (on one insect) for the postulated "swarm". This range is 3 x 333 m = 1 km.

It is interesting to compare the capabilities of this "man pack" radar with the AN/MPQ-4A radar which has been used in mosquito studies (see the paper by Emerson and Frost in these proceedings). Using the same radar cross-section for the cabbage looper-like moth as above, we find a detection range of 3.8 km for the single insect and a range in excess of 60 km for the swarm. Since the radar has a maximum display range of 15 km we note that such a swarm would produce good returns to the maximum range displayed by the larger radar.

It is likely that the most useful radar display will be a "B" scope or range-azimuth plot (this is somewhat similar to a sector PPI). Data records will be on a 35 mm motion picture film exposed one frame at a time. In automatic (unattended) operations exposures would be made at about 1 minute intervals. An operator could have active control of the exposure so that frames could be exposed whenever appropriate; multiple exposures could be made to give an insect path that would be seen as a series of bright spots forming a dotted line.

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[*]U.S. ground military radars use "mil" angular measurements. There are 6400 mils in a circle, that is 360° = 6400 mils or 1° $\approx$ 18 mils. In addition to equivalence with the traditional binary approach to "boxing the compass" the mil measurements are extremely useful trigonometrically since the tangent of a one unit angle is 1/1000. Stated another way, a pencil beam of one mil angle has a diameter of one meter at a range of one kilometer.

[**] $(\frac{1}{15})^4 \approx 2 \times 10^{-5}$; $\frac{5000 \text{ m}}{15} = 333$ m

Additions and modifications to the radar often emerge during a radar program. It is good to anticipate these. Two such features that may be valuable are: (1) an auxiliary vertical fan beam antenna ("cosec^2" - the existing antennas are pencil beam). This antenna gives a greater height average for close in targets. (2) a recording range gated-azimuth/amplitude or "waterfall display" with operation independent of the "B" display. The waterfall display could be viewed in real time with a X-Y scope or recorded sensitized paper.

Shared Time at Existing Facilities

Existing radar facilities, especially in Florida and Georgia, may be extremely useful for determining both incoming and outgoing insect populations and patterns for correlation with ground and aircraft trappings, and weather conditions. These data are needed to gain an improved understanding particularly of the longer-range movements of these insects. PPI photographs taken approximately every 15 minutes through the evening and early part of the night should be obtained as a minimum.

NASA is asked to take the lead in contacting the appropriate agencies to locate and obtain the use of these facilities. Short wavelength systems (X-band and below) are preferred, although most FAA and NWS systems are presently S-band (10 cm wavelength). A preliminary study will need to be conducted to determine the probability of detecting the Lepidoptera of interest with S-band systems.

Vertical Sounding Aircraft Mounted Radar

Fixed site radars are neither close enough together nor likely to be appropriately located for observing wide area insect migrations. In addition, it is probably not feasible to deploy sufficient mobile ground systems to monitor areas as large as the overwintering areas under consideration. It is therefore desirable to have a vertical sounding aircraft mounted radar available for this purpose. In order to secure data on the distribution and movement of insects, the system should be capable of using multiple range gates set at various depths below the aircraft. Such quantitative data has been impossible to obtain in any other way, but is necessary to narrow down as far as possible the areas, times, and techniques for intensified control/management operations.

Glen Schaefer (see number 41 in Selected Bibliography) has already used this technique to study the spruce budworm in Canada, and there appears to be no other fully comparable nadir-pointing system at present. Consideration should be given to demonstrating the Schaefer system in the United States.

However, a feasibility study, with follow-on field demonstrations, should be conducted to determine if the NASA/WFC radar altimeter and surface contouring radars can contribute to this effort.

Aircraft are expensive to fly, but a single aircraft with airborne radar as in Canada could give regular nightly coverage of the whole of the overwintering area of southern Florida, with insect height/density profiles every 10 m of travel along traverses only 30 km apart. Careful attention must be paid to the sampling strategy used; it is already known that in any given area insect flights are highly time dependent. Also, full use should be made of Doppler radar wind-finding equipment in the same aircraft to locate and explore zones of wind-convergence where moths are very likely to concentrate.

Laser Radar (Lidar) Techniques Evaluation

We propose that basic experiments be conducted to determine the potential of laser systems, either lidars or active fluorosensors, for detecting, tracking, or mapping the distribution of insects. One such experiment should include marking appropriate insects with a fluorescent dye (such as rhodomine) that is stimulated with a laser, and determining if they can be seen against the natural background with a spatially scanning receiver mounted in an airplane. Such a system, with the laser and receiver using common optics, already exists at Wallops Flight Center. Information from this experiment should then be used to assess the future role of this technique in the overall insect management problem. We suggest that one application of this technique, if successful, is to monitor the temporal change of the gross population distribution of sterile male moths that are dyed and released into a natural population.

Other experiments should include lidar applications to relatively short range, high resolution observations of insects near a plant canopy.

PERSONNEL TEAM

Any large scale pest management program that uses radar inputs must have a personnel team with a multidisciplinary composition. For the recent spruce budworm moth dispersal work in Canada, we noted that specialists with appropriate experience were required from three recognized disciplines: not only radar technology and applied entomology but also meteorology (with which Appendix B deals in more detail, since applied entomologists are relatively unfamiliar with it). In research and development work that integrates radar technology with pest management, we emphasize that the particular experience of each member of the multidisciplinary team is important. Appendix A outlines the skills of the

Canadian team members. Each specialist at least needs sufficient understanding and appreciation of the other specialities to be able to pose useful questions outside his own field while at the same time realizing his own limitations in attempting single-handed answers. In addition to these recognized disciplines, two other types of specialists are essential. The first may be termed a <u>dynamic biogeographer</u>, who undertakes the continuing collation, analysis, mapping, and integration of all available current information on the pest and its environment and who provides in real-time the current distribution and movements that are necessary to identify and restrict as closely as possible the appropriate times and places for intensive management operations. Because, in particular, of the inevitably incomplete and often fragmentary nature of the distribution and movement data that is available from the geographically extensive areas involved, human judgment remains essential for its assessment. The second somewhat novel type of specialist is the <u>airborne mission scientist</u> (already recognized in airborne meteorological research). Airborne radar is an immensely powerful tool for research and potentially for operational use, but its fullest exploitation cannot be entirely automatic. The airborne mission scientist is needed for in-flight monitoring, mapping, and preliminary interpretation of all data that is secured on the pest and on its atmospheric environment; and hence for the progressive amendment of the current flight plan whenever this becomes necessary to establish contact with the maximum proportion of the airborne pest population.

RECOMMENDATIONS

1. The group recommended recognition of the strategic winter control of the fall armyworm (and ecologically similar pests) in overwintering areas of the southern United States as a major economic problem on which radar could make unique, immediate, and probably crucial contributions to
    a. the location and assessment of the whole of the pest population involved and
    b. following its changing spatial distribution in real time, in order to
    c. identify times and places at which suppressive operations would be most effective in protecting the crops threatened by the spread of the next generation.
2. The group recommended pursuing these objectives by the co-ordinated use, as soon as possible, of three immediately available radar systems:
    a. small (man-portable) surveillance radars, for quantifying the emigration of emerging moths following heavy larval infestations and for securing echo-signatures of known target species; envisaged for routine use in numbers for monitoring and assessing moth emigration at points sited to sample all current major infestations,

  b. existing fixed site surveillance radars, for continuous monitoring particularly of coastal areas, and

  c. vertical-sounding aircraft-mounted radar - as developed by Schaefer at Cranfield, and used in Canada in conjunction with Doppler radar airborne wind-finding equipment - for systematic nightly sampling and assessment of the complete moth populations involved.

3. In addition, the group recommended feasibility studies:

  a. to explore the potential of laser systems (lidars, etc.) for mapping the distribution of individual insects using, for instance, the WFC Airborne Oceanographic system in a fluorosensing mode to detect either naturally-fluorescing or fluorescently-dyed insects and to determine basic signal strength relative to the natural background, and

  b. to determine if the NASA/WFC radar altimeter and surface contouring radars can contribute to the further development of aircraft-mounted insect detecting radar systems.

It was not felt appropriate to spend time on administrative questions at the expense of technical discussions, but, in view of the importance of the fall armyworm dispersal problem in particular, we hope that what has now been shown to be technically possible might also become administratively possible. Indeed, Appendix A gives an excellent example of the type of team and support needed for a reasonably comprehensive program in a considerably smaller region than would be involved in studying some of the migratory agricultural pests in the U.S.

SPRUCE BUDWORM MOTH DISPERSAL IN NEW BRUNSWICK, CANADA
(Methods, equipment, and manpower employed when operating with one radar unit.)

The spruce budworm moth period at any site in New Brunswick continues for 14 to 21 days. The following observations were made nightly at each radar site.

Observation Platform

Visual counts were made of the number of moths taking off and emigrating from a cluster of 10 trees. Counts made over two-minute periods at intervals of 5 minutes from 1930-2130 hours.

Using a night viewing telescope, counts were made of the number of moths taking off from the top of one tree during 30 seconds every 5 minutes. Counting began at 2000 hours and continued until all takeoff activity ceased after dark.

Samples of ascending and descending moths were collected each night before dark using hand nets.

Ground-Based Radar

Counts made of the number of echoes appearing on a portion of the PPI. The measurements were repeated for a series of elevation angles and, for the purpose of permanent record, a photograph was taken of the PPI image for each angle. A complete sequence of elevation angles required some 8 minutes and produced a height profile of budworm density.

The radar was in operation from 1930 until early a.m. or until number of echoes fell markedly and indicated dispersing moths were settling.

Aircraft Insect Collecting Net

An aircraft insect collecting net was designed by J. Spillman of Cranfield College of Aeronautics to sample and soft-land airborne insects. A single-engine Cessna 185 was used to sample above the observation platform at altitudes of 60 to 300 m. Flights began each night at 2000 and continued until after midnight. The flight path extended for 16 km on each side of the observation platform and lasted 10 minutes. The end cap of the collecting sleeve was changed at the end of each run while in flight.

Meteorological Tower

A transportable meteorological tower was set up within the forest close to the observation platform to monitor nightly meteorological conditions within and above the forest canopy. The sensing equipment was located at 2 m, 11 m (mid-crown) and 22 m (7 m above the tree tops). Wind speed, wind direction, and turbulence were measured with bivane sensors; wet and dry bulb temperatures by thermistors. A microbarometer was housed in a laboratory trailer along with a Nova 1220 computer connected to the sensor units. The computer was programmed to sample and print the mean values of each parameter at 2-minute intervals.

Pilot Balloon Releases

Slow-ascent pilot balloons carrying minisondes were released at hourly intervals each night at the radar site throughout the moth season. At some radar sites, an acoustic sounder recording the height of the inversion layer and a kytoon carrying meteorological sensing equipment were also used.

Aircraft Exploration of Wind-Systems

A DC-3 survey aircraft was equipped with a Bendix Doppler radar navigation and wind-finding equipment and air temperature and humidity recorders. The Bendix system was replaced with a Decca Doppler radar system in 1976 for compatability of frequency with the airborne insect detecting radar.

The DC-3 was flown for 2 to 4 1/2 hours each evening through the moth season over the Province of New Brunswick to explore wind systems and wind-shift features when encountered.

Estimating Current Fecundity of Dispersing Moths

All moths collected in nets while in exodus flight, moths collected by the aircraft, and moths collected after deposition out of the airspace were examined for sex, mating status, and number of eggs being carried.

Additional Monitoring Systems

These included the nightly operation of light traps, one in a clearing and two in the forest canopy. Pheromone traps were also used.

Weather Briefing

A meteorologist was responsible for keeping abreast of the synoptic situation and for briefing group leaders in the late afternoon. Wind patterns determine the direction of moth displacement. Ground temperatures at upwind source sites forecasts the time of night the moths will begin and terminate take-off activity. The flight plan for the DC-3 was fixed following this weather briefing.

Manpower

	Professional	Support
Co-ordinator	1	
Observation Platform	1 Entomologist	2
Ground-based Radar	1 Radar Engineer	3
Aircraft Insect Collecting Net	1 Pilot	1
Meteorological Tower	1 Meteorologist	1
Pilot Balloon Releases	1 Meteorologist	2
DC-3 Exploration of Wind System	2 Pilots (Captain & Co-Pilot)	
	1 Survey Navigator	1 Ground Engineer
	1 Flight Electronics Engineer	1 Data Processor
	1st Airborne Mission Scientist (Meteorological/Entomologist)	
	2nd Airborne Mission Scientist (Biogeographer)	
	[2 Airborne Radar Operators in 1976]	
Laboratory Analysis of Collected Moths	1 Entomologist	3
Weather Briefing & Synoptic Analysis	1 Meteorologist	
Additional Monitoring	1 Meteorologist	3
Total	15 + [2]	17

APPENDIX B

METEOROLOGICAL SUPPORT

Meteorological support has now become a clearly essential component of any insect flight dispersal study. The atmosphere is a dynamic system whose state cannot be controlled during the period of a study and, therefore, must be documented coincidentally with the insect behavioral study. Furthermore, the atmospheric state affects the transmission and reflection characteristics of radar; therefore, documentation of its state is similarly required for intelligent interpretation of the radar data.

Assuming the study consists of four phases - planning, design, conduct of the exercise, and analysis of the findings - it is essential that meteorological support be provided for all four phases. An illustration is given of the possible application of this support to the fall armyworm dispersal problem in southern and eastern United States.

Planning

The planning phase requires a review of dispersal patterns from historical evidence, to relate these patterns to historical weather circumstances. In particular, during periods of known movement of insects northward, the meteorological investigation should include an examination of

1. existence and frequency of wind vectors in the direction of the documented movement from (i) surface weather stations, (ii) surface weather chart analysis, and (iii) upper air stations;

2. occurrence of closed low pressure systems passing through the region of known adult infestation, with a component of northward motion. The convergence of such systems and the net upward motion within their centers, may provide mechanisms for single-event long-range transport;

3. occurrence of northward moving thunderstorms, especially in line squalls such as frequently accompany cold frontal passages. The analyst must be alert to the difference in direction of motion of a frontal system and of the individual storm cells. It is those individual cells which are -- or may be -- responsible for the dispersal as they progress in their life history from an active updraft to an active downdraft stage in a period of an hour or less. The best documentation of these systems will be from weather radar reports (available from the National Weather Records Center, NOAA, Asheville, North Carolina).

Generally, the analyst should only consider the time of day of known moth flight·activity.

This preliminary analysis of possible dispersal mechanisms, in addition to providing some detailed basic weather information specific to the problem, may provide clues about the mechanisms that require further detailed study.

The opportunity for an extended preliminary study may be limited, but even a superficial study would have some value in better defining the overall problem. Consultation between the insect ecologist (who would reasonably be expected to be co-ordinating such a project) and the meteorologist would extract the significant elements from this study to be incorporated into the design of the field study·project to follow. Not only would this advice be relevant to the design of the meteorological network, but it would also be relevant to other decisions such as the siting of pheromone traps.

Design

Meteorological advice is required in the design phase of a project to determine both the spatial and temporal dimensions of supplementary observing networks and the resources required to operate these networks. Such advice includes specifying the numbers and qualifications of field personnel and the type of equipment, its deployment and operating schedules.

It is apparent that meteorological data are needed at crop level to correlate with moth take off. This would include measurements of temperature, humidity, wind, light intensity, and perhaps the beginning of dew formation. It is furthermore likely that an instrumented tower, probably 10 m high, is necessary to obtain low level profiles of temperature, wind speed and direction.

Higher level profiles of temperature, wind speed and direction are needed from a network of stations throughout the area where the moths are anticipated to be transported. These may be in a fixed network, or -- more probably -- in a mobile network whose setup is determined in accordance with each evening's meteorological character. In particular, evidence from the New Brunswick spruce budworm moth dispersal study suggests that the thermal discontinuity at sea coasts initiates disturbances in the evening wind-field that are highly significant to the redistribution of airborne.moths. Most of the area under consideration can be affected by these disturbances, which may extend 100-500 km inland on some occasions.

Although supplementary networks of upper air stations of the minisonde (temperature and wind) type would probably be needed, it would be obviously desirable to establish their locations in a way to take advantage of regular upper air stations operated by the National Weather Service. Some of these NWS stations could probably be usefully requested

to provide more detailed and/or more frequent observations to assist the project.

The height to which upper air data are obtained should be well above the expected ceiling of moth flight, to at least 2000 m. The level of the nocturnal inversion is lower than this, likely no higher than 1000 m during the time moths are airborne, but features of the higher atmosphere may be of interest as well. In particular, the east coast of the USA experiences a nocturnal low level jet which may transport a small proportion of airborne insects to considerably greater distances than the bulk of the population.

Another supplementary network of some value is ground level stations equipped with microbarograph and thermohygrographs.

It is important to note that regular hourly weather observations are available from a network of National Weather Service stations that are located at intervals of about 50 km, usually at commercial and military airports. Such observations are transmitted hourly on weather service teletype network.

An even denser network of climatological stations is provided by volunteer observers who record daily total precipitation and maximum and minimum temperature. These data are reported monthly to the National Weather Service. Although such data are not normally available until after the end of a given month, they may be valuable for later analysis.

The tracking of thunderstorm cells would be an important element of the meteorological program. Tracks would be available directly from the photographic record from any insect radar used in the study, but should be supplemented by data from weather radar operated by the National Weather Service. Arrangements can be made to obtain photographic records from these stations.

Conduct of the Exercise

At least two professional meteorologists with distinctly different specializations should be involved in the conduct of a field exercise:

1. A research micrometeorologist with a thorough knowledge of boundary layer processes and some acquaintance with entomology. This meteorologist would design and supervise the operation of the field data program. If the project is extensive enough, two such meteorologists might be needed.

2. A synoptic meteorologist with local forecasting experience to provide continuing advice to the project co-ordinator on the current meteorological situation in the area. This meteorologist may be from the staff of the "local" weather office, but should not be encumbered with other regular duties at the time of the exercise, since a special, dedicated and detailed weather analysis program is needed up to the time of beginning of each evening's exercise with a thorough daily weather briefing given by this meteorologist and attended by most of the supervisory participants.

A daily de-briefing session would obviously be a part of the general project operating procedures, in order to monitor the progress of the exercise. Both the micrometeorologist and the synoptic meteorologist would contribute substantially to the value of these sessions.

Analysis of the Findings

The intensive data collection period must be followed by an extended period of analysis. Here, again, it is important that meteorological expertise be applied, and that the different specializations be recognized. Interpretation of the meteorological data should not be left to the entomologist; interpretation of synoptic meteorological data should not be expected of the micrometeorologist, nor vice versa.

Subsequent synoptic analyses should be conducted for each dispersal case of significance. The New Brunswick study showed that data about insect distribution, collected during the project, can provide information about detailed synoptic features that escaped notice at the time of initial (operational) analysis, but whose structure could be established on re-analysis.

Yet another type of meteorological expertise may be applied during the analysis phase -- that of the dynamic meteorologist who could construct trajectory analysis for insect dispersal using the combined insect/meteorological data in conjunction with other relevant data about the state of the atmosphere obtained from other sources, e.g., radar. These particular tasks may be undertaken by one of the meteorologists who took part in earlier phases of the project -- but it is the analytical skill rather than project experience which is important.

SCIENTIFIC AND COMMON NAMES OF REFERENCED INSECTS

fall armyworm	*Spodoptera frugiperda* (J. E. Smith)
beet armyworm	*Spodoptera exigua* Hübner
velvet bean caterpillar	*Anticarsia gemmatalis* Hübner
corn earworm	*Heliothis zea* (Bodie)
tobacco budworm	*Heliothis virescens* (F)
soybean looper	*Pseudoplusia includens* (Walker)
cabbage looper	*Trichoplusia ni* (Hübner)
greenbug	*Schizaphis graminum* (Rondani)
screwworm	*Cochliomyia hominivorax* (Coquerel)
pink bollworm	*Pectinophora gossypiella* (Saunders)
green peach aphid	*Myzus persicae* (Sulzer)
-------	*Lygus hesperus* Knight
boll weevil	*Anthonomus grandis* Boheman
gypsy moth	*Lymantria dispar* (Linnaeus)

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ENTOMOLOGY AND PEST MANAGEMENT

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The wingbeat rate of many insects has been shown to vary with other physiological aspects of flight. The variability of the wingbeat rate of an individual insect is important to radar scientists that wish to devise species discrimination techniques; while, the insect physiologist may find interesting the capability of radar to determine the wingbeat rate of free-flying insects and hence infer other physiological events that correlate with this rate. Several entries to the literature of this subject include:

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RADAR TECHNOLOGY

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62. Fell, B., 1978: "An Introduction to Radar Concepts," RCA Engineer 23, No. 5, 14-24.

The next three texts are written from the data user's point of view; emphasis is on what the radar measures and how the data can be interpreted. Most relevant to entomology is the Eastwood book, although it is dated both in terms of what radar can actually tell about individual birds and in the presentation of radar data processing and display capabilities.

63. Battan, L. J., 1973: _Radar Observations of the Atmosphere_, The Univ. of Chicago Press, Chicago, x+324 pp.
64. Eastwood, E., 1967: _Radar Ornithology_, Methuen & Co., Ltd., London, xii+278 pp.
65. Long, M. W., 1975: _Radar Reflectivity of Land and Sea_, Lexington Books, D. C. Heath and Co., Lexington, Mass., xxvi+366 pp.

For those wanting to go deeper into the engineering aspects of radar and the processing of radar signals the four following texts should be sufficient.

66. Skolnik, M. I., 1962: _Introduction to Radar Systems_, McGraw-Hill Book Co., Inc., New York, ix+648 pp.
67. Skolnik, M. I., 1970: _Radar Handbook_, McGraw-Hill Book Co., Inc., New York, 39 chaps.
68. Barton, D. K., 1974: _Radars_, Artech House, Inc., Dedham, Mass., 5 Volumes.
69. Nathanson, F. E., 1969: _Radar Design Principles. Signal Processing and the Environment_, McGraw-Hill Book Co., New York, xiii+626 pp.

Radar meteorology has advanced to the stage where it appears to be a distinct self-supporting discipline. Both system design, and data interpretation and analysis are actively pursued from the user point of view. State-of-the-art developments in this discipline can be expected to contribute to radar, entomology. The past five, or so, of the following seventeen conferences are useful in this regard.

70. American Meteorological Society. - <u>Conference</u> <u>on</u> <u>Radar</u> <u>Meteorology</u> <u>of</u> <u>the</u> <u>American</u> <u>Meteorological</u> <u>Society.</u>

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