Microwave Radar Detection of Stored-Product Insects

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ABSTRACT A microwave radar system that senses motion was tested for capability to detect hidden insects of different sizes and activity levels in stored products. In initial studies, movements of individual adults or groups of *Lasioderma serricorne* (F.), *Oryzaephilus surinamensis* (L.), *Attagenus unicolor* (Brahm), and *Tribolium castaneum* (Herbst) were easily detected over distances up to 30 cm in air. Boxes of corn meal mix and flour mix were artificially infested with 5–100 insects to estimate the reliability of detection. The likelihood that a box was infested was rated by the radar system on a quantitative scale. The ratings were significantly correlated with the numbers of infesting insects. The radar system has potential applications in management programs where rapid, nondestructive targeting of incipient insect infestations would be of benefit to the producers and consumers of packaged foods.

KEY WORDS packaged goods, Termatrac, precision targeting, nondestructive detection

CONSUMERS EXPECT MANUFACTURERS to keep packaged food products free of insect infestation (Highland 1984). However, manufacturers and retailers currently have only limited capability to detect infestations after the products have been processed and packaged (Chambers 2003). Noninvasive technologies are of particular interest as insect detection tools that may increase the effectiveness of management activities while reducing costs for retailers and pest control professionals (Weier 2003). In addition, heightened awareness of the risks of chemical pesticides has increased the need for tools that help managers target insecticide applications precisely to infested areas (Arbogast et al. 2000). Radar is a noninvasive, precision targeting technology that has not yet been applied to detect stored-product insects, although it has been used for decades to monitor insect migration (for review, see Reynolds and Riley 2002).

A microwave radar system was developed recently with the capability to detect hidden infestations of termites (Tirkel et al. 1997, Evans 2002, Korb 2003). The principle of operation is similar to that of radar systems used to monitor movement of wind and rain in storm systems (Edde 1993, Riley and Smith 2002). Through a Doppler effect, the frequency of radar reflected from a moving insect is slightly higher than the emitted frequency when the insect moves toward the receiver. The reflected frequency decreases slightly when the insect moves away from the receiver. Movements of objects as small as insects or raindrops can be detected as a difference between the emitted and reflected radar frequencies. Termite detection devices are now being distributed in the United States (Termatrac, Protecusa, Coral Gables, FL). The Termatrac emits a fixed frequency microwave beam from a 5 by 6.5-cm horn and measures the intensity and frequency of signals reflected back to a collocated receiver (Tirkel et al. 1997, Protecusa 2002). A signal processor computes the intensity of the reflected energy and the difference between emitted and reflected frequencies, and displays the result on a front-panel liquid crystal display (LCD).

To consider potential applications of microwave radar for detection of hidden infestations of stored-product insects, a Termatrac device was tested in bioassays with adults of four different stored-product insect species of different sizes and activity patterns. The smallest insect was the 2–3-mm-long cigarette beetle, *Lasioderma serricorne* (F.), a major pest of flour and other stored food products (Krischik and Burkholder 1995). Cigarette beetles are relatively inactive, particularly when disturbed (Howe 1957). The sawtoothed grain beetle, *Oryzaephilus surinamensis* (L), a cosmopolitan invader of packaged consumer food (e.g., Arbogast 2003), is 3 mm in length and moderately active. The black carpet beetle, *Attagenus unicolor* (Brahm), an important museum pest (Su and Scheffrahn 1990), is 3–6 mm in length and moderately active. The red flour beetle, *Tribolium castaneum* (Herbst), a major pest in flour mills and retail stores (Campbell and Runnion 2003), is 3–4 mm in length and is one of the most mobile stored-product insect pests.

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Materials and Methods

Insects. *O. surinamensis*, *L. serricorne*, and *T. castaneum* were obtained from colonies maintained at the USDA–ARS Center for Medical, Agricultural, and Veterinary Entomology (CMAVE), Gainesville, FL (Mankin et al. 1997a). *A. unicolor* were obtained from the USDA–ARS Grain Marketing and Production Research Center, Manhattan, KS. The insects of different species were held separately in 900-ml glass rearing jars containing rearing medium, 200–300 adults per jar, at 26°C and 55% RH until they were used in bioassays.

Radar System Operating Characteristics. The Termatrac was not expected to operate over distances >1–2 m (Tirkel et al. 1997), and the radar beam was not expected to pass through metal or substrates with high moisture content (Protecusa 2002). Otherwise, very little was known in advance about the range and sensitivity of the Termatrac with stored-product insects. Consequently, several preliminary positioning experiments with visible groups of *A. unicolor* and *O. surinamensis* were conducted to determine the approximate detection range and field of view (see below).

The Termatrac's sensitivity to insect motion is user-settable to one of seven different levels to accommodate differences in substrate absorptivity (a relative measure of the ability to absorb microwave energy) and differences in the size and speed of the insects (Protecusa 2002). The control defaults to midrange, level 3, for general use. The receiver can detect motion or vibration by any object in the field of view whose dielectric constant (a relative measure of the capability to store electric charge) differs from that of the substrate (Edde 1993). To achieve the greatest sensitivity to insects, the receiver must be held still during testing and, if possible, moving objects not of interest must be removed from the field of view. The bioassays in this study were conducted in a vibration-shielded anechoic chamber backed by a metal wall (Mankin et al. 1997b).

Preliminary investigations with 200–300 *L. serricorne* in jars and packages of corn meal mix (see below) suggested that midrange, level 3, was appropriate to assess insect movement in open containers, and maximum sensitivity, level 6, in packaged goods. The appropriateness of these settings was confirmed in subsequent, more detailed bioassays.

Bioassays with Visible Insects. The first bioassays were conducted with rearing jars or 8.7-cm-diameter by 1.5-cm-high petri dishes containing *A. unicolor*, *L. serricorne*, or *O. surinamensis* adults. The petri dishes contained a single active adult or 20 adults of a given species. Empty jars and petri dishes, and jars containing uninfested rearing medium were tested as controls. The Termatrac sensitivity was set at midrange, and the petri dishes were placed at the horn axis, with the near edge 3 cm from the horn. In a trial to estimate the field of view, a petri dish containing 20 *O. surinamensis* adults was tested at six positions along the axis, with the near edge 3, 9, 13, 18, 23, or 30 cm from the horn. A second petri dish with an adult *L. serricorne* was tested 0, 4, 5, and 6 cm from the horn axis, 3 cm from the horn.

The Termatrac indicates motion within its field of view by means of a bar on an LCD display. It became apparent early in the bioassays that the Termatrac readings were highly variable over short time scales and could not be easily characterized by simple visual assessment of the LCD display. To assess the variability, the LCD display was recorded with a digital camera (Nikon Coolpix 990, Nikon Inc., Melville, NY) and observed frame by frame during several periods where insect movement was visually monitored. Maximum and minimum readings were noted for each 1-s interval, measured as the maximum and minimum deflection of the LCD bar in millimeters. In general, the maximum readings seemed to be more representative of the observed insect motion than the minimums. The peak readings, i.e., the maximum deflections in each 1-s interval, were graphed on a linear scale and on a dB (decibel) scale (e.g., Mankin 1994), where movement level was calculated as movement level = 20 log10 (peak reading). The maximum deflection on the LCD scale was 3.7 cm, corresponding to a movement level of 31 dB.

Visual Assessment of the Likelihood of Infestation. The process of recording and analyzing the instantaneous output of the Termatrac ultimately provided limited information beyond what could be observed by visual assessment of the bar activity. To develop a rapid alternative to the video analysis, we developed a rating scale to visually classify readings into different infestation likelihood categories. A similar, auditory rating scale is used currently for rapid, qualitative assessment of subterranean insect infestations (e.g., Mankin et al. 2001, Zhang et al. 2003).

The scale was subdivided into three categories. If the movement level remained at 0 dB during a 15-s observation interval, the likelihood that a container was infested was rated low (0 on a numeric scale). If movement levels exceeded five dB at least once during a 15-s observation interval, the likelihood of infestation was rated medium (1 on a numeric scale). If movement levels exceeded 10 dB, or if 5-dB or higher fluctuations occurred more than three times during the 15-s interval, the likelihood of infestation was rated high (2 on a numeric scale). The numeric rating of infestation likelihood essentially was logarithmic because, for classification purposes, a small change in the movement level at low dB was considered as important as a large change in movement level at high dB.

Bioassays with Hidden Insects. Initially, five 240-g boxes of corn muffin mix (13.8 by 7.6 by 4.3 cm) and five 567-g boxes of all-purpose flour mix (19.2 by 12.2 by 5.1 cm) were preinfested with 0, 10, 20, 50, or 100 *O. surinamensis*. For testing, a box was set adjacent to the horn, with the Termatrac operating at sensitivity level 6. Over a 2-min period, the box was moved systematically through six different positions so that each face of the box was set next to the horn for approximately a 15-s monitoring interval. Using criteria based on the movement level readings, described above, the likelihood of infestation was rated visually as low, medium, or high at the position that yielded the highest movement level readings. Each of the 10 boxes was monitored five times daily over a 10-d period (excluding weekends). When the series was completed, the boxes were reopened and the insects were recounted. All of the introduced insects were recovered from the sifted contents and were alive.

The results of the initial hidden insect bioassay (see Results below) suggested that infestations smaller than 10 insects might be detected reliably by the Termatrac. This possibility was tested in a preliminary study with boxes of corn meal mix artificially infested with 0, 1, 2, 5, and 10 *O. surinamensis* adults. Infestations as small as one to two adults were detectable, but not necessarily in every 2-min observation period. Boxes with five insects, however, registered movement in almost every observation period.

A series of tests similar to the initial 10-box *O. surinamensis* bioassay was conducted with *T. castaneum,* with the addition of a box of corn meal mix artificially infested with five adults. The 11 boxes were monitored five times daily over a 13-d period as described above. When the series was completed, all of the introduced insects were recovered from the sifted contents and were alive.

Statistical Analyses. Regression analysis (SAS Institute 1988) was used to examine the effects of the numbers of insects in the field of view on the rating of the likelihood of infestation. Because the numeric rating of the likelihood of infestation was set essentially on a logarithmic scale (see Results), the insect numbers also were logarithmically transformed as log10 (no. insects +1). In the transformation, the number of insects was offset by one so that the ratings of control boxes with no insects could be shown at zero on a graph of likelihood rating against transformed numbers of tested insects. The regression equation was as follows: numeric infestation rating = $A + B$ log10 (no. insects +1), where A is the intercept on the rating axis, and B is the slope.

Results and Discussion

Two different types of bioassays were conducted in this study, one that enabled direct visual comparison with radar observations, and one where insects were hidden inside artificially infested packages of corn meal or all-purpose flour mix. Both series of bioassays, conducted with insects of different sizes and behavioral activities, confirmed that microwave radar systems could measure stored-product insect movement in a variety of circumstances.

Bioassays with Visible Insects. Examples of Movement Levels in 30-s recordings from jars and petri dishes containing different numbers of *A. unicolor* and *L. serricorne* are shown in Figs. 1 and 2. Because these tests were conducted in a vibration-shielded chamber, Movement Levels were zero when insects were not present in the field of view. In tests with individual adults in petri dishes, changes in movement level were easily interpretable as changes in observable motion.

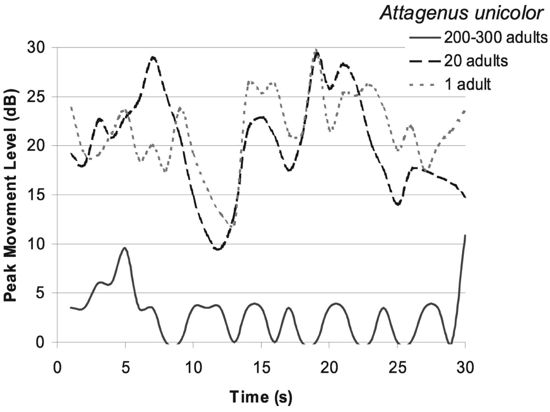

Fig. 1. Movement levels of an individual *A. unicolor* adult in a petri dish, 20 adults in a petri dish, and a jar with 200–300 adults monitored by microwave radar.

It was more difficult to discern clear relationships between movement level and observable motion when 20 adults were present in a petri dish. In general, a dish with 20 insects was perceived visually to have greater motion than a dish with one insect, but movement levels ranged generally between 10 and 25 dB irrespective of the number of insects. Similarly, when the radar was trained on a rearing jar, movement levels did not necessarily increase in proportion to visually perceived motion. In Fig. 2, movement levels of *L. serricorne* were comparable for a rearing jar of 200–300 adults, a petri dish with 20 adults, and a petri dish with one adult. In Fig. 1, a rearing jar with 200–300 *A. unicolor* had lower movement levels than a petri dish with one adult. However, the experimental conditions make these results difficult to compare directly because the insects in the jars had less freedom of movement than in the petri dish, and multiple reflections from large numbers of insects can interfere with each other. In addition, not all insects were moving at all times.

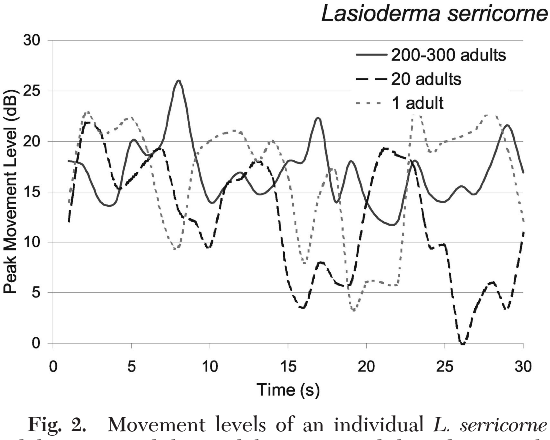

Fig. 2. Movement levels of an individual *L. serricorne* adult in a petri dish, 20 adults in a petri dish, and a jar with 200–300 adults monitored by microwave radar.

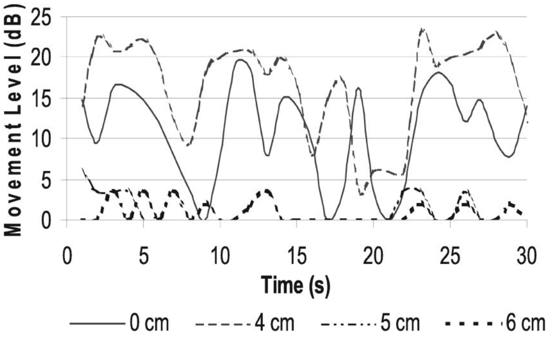

Fig. 3. Movement levels of an individual *L. serricorne adult* in a petri dish offset 0, 4, 5, or 6 cm from the microwave radar horn axis.

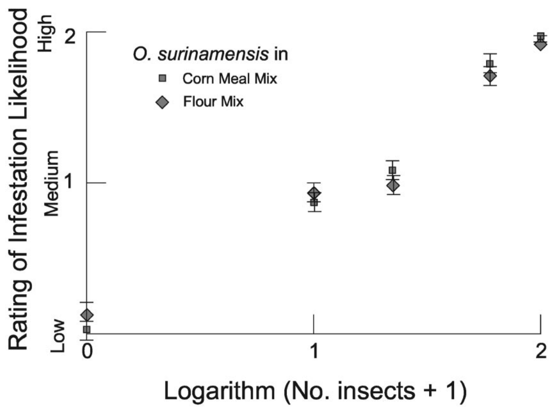

Fig. 4. Ratings of infestation likelihood (mean ± SE) for boxes of corn meal mix and flour mix, uninfested or artificially infested with different numbers of *O. surinamensis*, monitored by microwave radar.

There was considerable variability in the preliminary study of motion by 20 adult *O. surinamensis* in a petri dish, 3, 9, 13, 18, 23, and 30 cm from the Termatrac horn. The magnitude and frequency of the Termatrac readings tended to decrease with increasing distance, but movements were detectable at all six positions.

The sensitivity of the Termatrac to insect movement away from the axis did not seem to decrease until the insects were placed near the edge of the field of view (Fig. 3). Movement Level readings from a petri dish with an adult *L. serricorne*, 3 cm from the edge of the Termatrac base, ranged between 10 and 25 dB until the dish was offset 5 cm or more from the horn axis. The total width of the field of view above and below the axis was thus ≈10 cm.

Visual Assessment of the Likelihood of Infestation. In general, it would be impractical to assess the presence or absence of insects in packaged goods by recording the Termatrac output and calculating movement levels. The process is time-consuming and provides limited information beyond what can be observed by visual assessment that motion is absent, barely detectable, or obviously present. A more rapid procedure developed from an initial observation that insects in packaged goods typically move more slowly and over shorter distances than in a more open environment of a rearing jar or petri dish. In the preliminary studies with boxes of corn muffin mix containing five or fewer insects, the Termatrac usually registered only a few, 3–6-dB movements during a 2-min observation session. Even with 50–100 insects, movement levels rarely exceeded 10–15 dB. These observations led to development of the visual assessment scale (see Materials and Methods) that was tested in subsequent bioassays below.

Bioassays with Hidden Insects. The visually assessed ratings of infestation likelihood were graphed against the transformed numbers of adults inside boxes of corn meal and flour mix in Fig. 4. Readings from the boxes infested with 50 or more *O. surinamensis* consistently indicated a high likelihood of infestation. Boxes infested with 10 or 20 *O. surinamensis* rated primarily at a medium likelihood of infestation. In tests with uninfested boxes of corn meal mix or all-purpose flour mix, the LCD bar registered briefly above baseline in 12% of uninfested flour mix readings and 2% of corn meal mix readings. Otherwise, the uninfested boxes were rated at a low likelihood of infestation. Such excursions from baseline were not observed in readings from empty jars or petri dishes. They may have been caused by settling of the box contents, which has been observed previously in acoustic detection studies of stored-product insects (Mankin et al. 1997b). Regressions of the rating of infestation likelihood on the transformed numbers of *O. surinamensis* (Table 1) were statistically significant for tests in corn meal ($F = 1358.35$; df = 1, 248; $P < 0.001$; $r^2 = 0.85$, residual mean square error = 0.091) and flour mix ($F = 651.86$, df = 1, 248; $P < 0.001$, $r^2 = 0.72$, residual mean square error = 0.158).

It should be noted that the procedure of repositioning the boxes so that each face was presented to the Termatrac horn was an important factor in the success of the bioassays with hidden insects in corn meal mix. The repositioning had two effects. First, it caused a disturbance (Mankin 2002) that elicits movement of *O. surinamensis* and *T. castaneum* adults. Second, it circumvented a problem caused by the limited capability of the radar to travel through corn meal or flour mix.

Before the hidden-insect bioassays, six preliminary tests were conducted to consider the potential effects of corn meal mix on the radar signal. Termatrac readings were monitored with and without boxes of corn

Table 1. Regression coefficients (see Materials and Methods) for relationship between numeric rating of infestation likelihood and the transformed numbers of *O. surinamensis* infesting boxes of corn meal mix and flour mix

Substrate	Coefficient	Estimate	Standard error	*P*
Corn mix	*A* (intercept)	−0.062	0.039	0.1107
	B (slope)	1.02	0.028	<0.001
Flour mix	*A* (intercept)	0.034	0.051	0.5047
	B (slope)	0.930	0.036	<0.001

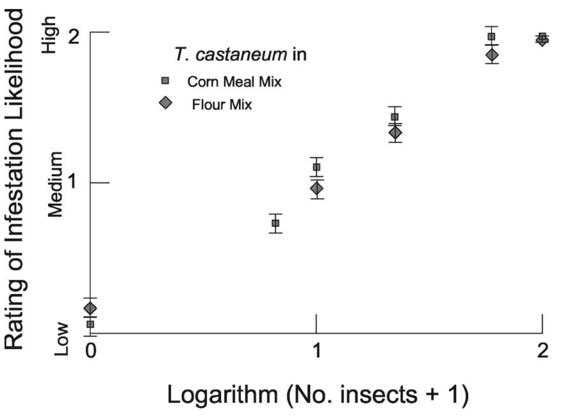

Fig. 5. Ratings of infestation likelihood (mean ± SE) for boxes of corn meal mix and flour mix, uninfested or artificially infested with different numbers of *T. castaneum*, monitored by microwave radar.

muffin mix between the horn and petri dishes containing 20 adult *O. surinamensis.* Readings also were monitored when empty boxes were placed between the horn and the insects. The Termatrac registered a response in only one of the six tests with an interposed box but always registered a response when the box was removed. It also registered a response in all tests where an empty box was interposed. This suggests that repositioning of an infested box enabled insects at or near the edge of the box to be detected at the repositioned face even if the signal could not pass completely through the box.

Other stored-product substrates might also absorb microwaves significantly, depending on their densities and moisture levels. The Termatrac manual (Protecusa 2002) has noted, for example, that the microwave radar does not transmit well through moisture-laden substrates. Interior wooden structures that are typical substrates for Termatrac testing have moisture contents of 6–11% (Simpson 1999), whereas wheat flour has a somewhat higher moisture content of 11–14% (Samuels and Modgil 1999). Flour has a bulk density of 593 kg/m^3, whereas different woods have densities ranging from 170 to 500–600 kg/m^3 (e.g., http://www.simetric.co.uk/si_materials.htm).

The success of the trials with *O. surinamensis,* led to an additional study with highly mobile, adult *T. castaneum.* As with the boxes artificially infested with 10 or 20 adults (Fig. 5), the boxes with five adults were rated at medium likelihood of infestation. However, the rating of 0.78 with five adults in the corn meal mix was lower than the rating of 1.17 with 10 insects. As in tests with *O. surinamensis,* boxes of either corn or flour mix artificially infested with 50 or 100 adults were rated at a high likelihood of infestation. Regressions of the rating of infestation likelihood on the transformed numbers of *T. castaneum* (Table 2) were statistically significant for tests in corn meal ($F = 1554.54$; df = 1, 388; $P < 0.001$; $r^2 = 0.80$, residual mean square error = 0.114) or flour mix ($F = 892.91$; df = 1, 324; $P < 0.001$; $r^2 = 0.73$, residual mean square error = 0.158).

Table 2. Regression coefficients (see Materials and Methods) for relationship between numeric rating of infestation likelihood and the transformed numbers of *T. castaneum* infesting boxes of corn meal mix and flour mix

Substrate	Coefficient	Estimate	Standard error	P
Corn mix	*A* (intercept)	0.039	0.035	0.2617
	B (slope)	1.03	0.026	<0.001
Flour mix	*A* (intercept)	0.109	0.044	0.0147
	B (slope)	0.953	0.031	<0.001

Potential of Microwave Radar Detection Tools in Stored-Product Insect Integrated Pest Management (IPM) Programs. Microwave radar systems are not yet generally available for use in nondestructive targeting of stored-product insect infestations in retail stores and storage facilities. The results of this study indicate, however, that such devices have the capability to nondestructively detect small numbers of insects hidden in packages, and they could be used to assist pest managers and researchers who now rely primarily on traps to target incipient infestations. As with currently available acoustic technology (Mankin et al. 2000), these systems operate over limited distances, which facilitates the targeting of infestations.

Microwave radar technology also is similar to acoustic technology in that both require the insects to move before they can be detected. This requirement restricts the use of both technologies to environments where the temperatures are high enough to support insect movement. Some insects become quiescent when disturbed (Mankin 2002), in which case it would be preferable to delay measurements for a 5–10-min period after setting a box next to the horn. *O. surinamensis* and *T. castaneum* did not become quiescent during the disturbances caused by reorienting different faces of a box next to the horn. Their activities were usually greatest just after the disturbance.

Another similarity between microwave and acoustic detection technology is that both systems must be shielded from background activity. Shielding is of most concern in cases where the infestation levels or temperatures are low because this is when the signal levels are lowest relative to background activity. Suggestions for proper shielding and interpretation of Termatrac readings have been developed for termite detection programs (Protecusa 2002), but additional experiments in commercial facilities will help determine whether special precautions will be necessary to avoid spurious measurements in stored-product environments.

An application where microwave radar may have an advantage over acoustic technology is in its potential for high-volume sampling. Acoustic systems are not easily adapted to high-volume sampling because considerable space is required for background noise insulation. Modifications of currently available horns and receivers may enable future development of systems that rapidly screen multiple packages as they are moved into a storage or retail facility. Knowledge of the behavior of the insects targeted for detection and understanding of the operating characteristics of the microwave radar systems could assist in the success of such monitoring efforts. For example, if the target insects tend to settle near the tops of the internal contents of the packages, the horn could be directed between the tops of the packages and the internal contents. This increases the likelihood of detection and reduces radar transmission losses.

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