*Journal of the American Mosquito Control Association*, 10(2):302–308, 1994

# ACOUSTICAL DETECTION OF *AEDES TAENIORHYNCHUS* SWARMS AND EMERGENCE EXODUSES IN REMOTE SALT MARSHES

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ABSTRACT. Swarms and emergence exoduses of *Aedes taeniorhynchus* mosquitoes produce sounds detectable from 10 to 50 m in a quiet environment. Background noise levels as low as 21 dB (decibels referenced to 20 μPa) are present at dusk between frequencies of 0.3 and 3.4 kHz. A mosquito swarm with a sound pressure level of 25–35 dB is detectable over tens of meters in the marsh, if not in the 40–60-dB background noise of a typical urban environment. Individually caged *Ae. taeniorhynchus* also are detectable, but only within 2–5-cm distances where the sound pressure level rises to 22–25 dB. These differences between signal and noise levels indicate that it is technologically feasible to construct an acoustical device for remote surveillance of large swarms or emergence exoduses of *Ae. taeniorhynchus*. This device could also detect nearby individuals attracted to a bait. Such a device can distinguish males from females by their wingbeat frequencies (700–800 Hz vs. 400–500 Hz).

## INTRODUCTION

Swarming male mosquitoes identify nearby conspecific females by the sounds of their wingbeats (Roth 1948, Clements 1963). Acoustical technology thus has been of interest as a potential tool for mosquito trapping, surveillance, and identification (Offenhauser and Kahn 1949, Belton and Costello 1979, Ikeshoji 1981, Ikeshoji et al. 1985, Moore et al. 1986, Ogawa and Kanda 1986, Kanda et al. 1987, Ogawa 1988). The major impediment to development of acoustical detection or surveillance techniques is that the low intensity of wingbeat sounds makes them difficult to detect above background noise except in the laboratory (Nielsen and Greve 1950, Jones 1964). The best chance of field surveillance is in a quiet area where there is a high mosquito population such as the southwestern Florida Everglades. High populations of *Aedes taeniorhynchus* (Wied.) erupt frequently in coastal marshes after heavy summer rains and high tides (Nayar 1985). Newly emerged adults can migrate in a sometimes audible exodus at sunset (Nielsen and Haeger 1959). Likewise, swarms are audible when large groups of males collect near emergence sites at sunset (Haeger 1960). Identification of emergence and oviposition sites is important for successful direction of control efforts (Ritchie et al. 1992, Ritchie 1993).

This report describes a study to determine the feasibility of acoustically detecting mosquitoes in remote areas where automated surveillance is cost-effective. It addresses 3 major questions: 1) What is the *Ae. taeniorhynchus* wingbeat spectrum and sound pressure level (SPL)? 2) How do mosquito SPLs in the natural habitat relate to background noise levels? 3) What signal processing technology is required to detect mosquitoes in the natural habitat?

## MATERIALS AND METHODS

*Aedes taeniorhynchus* were obtained from a laboratory colony kept by Dan Kline at the U.S. Department of Agriculture Medical and Veterinary Research Laboratory (MAVERL), Gainesville, Florida. Wingbeats of males and females, 1–2 h, 1–3 days, or 4–6 days postemergence were recorded with a microphone hung 3 cm over a 37 × 37 × 50-cm holding cage at 24°C and 78% RH.

Male *Ae. taeniorhynchus* swarm inside a holding cage for 0.5–2 h after each transition in a 12:12 h light : dark cycle. Several recordings were made of 500 swarming males, 2–3 days postemergence. To determine if there were any differences in the wingbeats of confined and unconfined swarms, individuals flying in a swarm of 10–15 male *Ae. taeniorhynchus*, 5 days postemergence, were recorded at dusk in a 18 × 8.5 × 4.9-m screened cage at 25°C and 92% RH.

Field recordings were made at Rookery Bay National Estuarine Research Reserve, Brush Key, and Marco Island, near Naples, FL, and at Flamingo, FL, in the Everglades National Park. Temperatures were 22–28°C, warmest at Rookery Bay and Flamingo, and coolest at Brush Key, where rain had just occurred. Each 2-h recording began just before sunset to include the peak flight period at dusk (Nayar 1985). An octenol source (Takken and Kline 1989) was taped to the microphone to attract adult females at both Rookery Bay and Flamingo. Prior reconnaissance indicated that emergence exoduses were likely during the recordings at Rookery Bay, Marco Island, and Brush Key.

Recordings in the laboratory were made with a B&K Model 4145 microphone connected to a B&K Model 2639 preamplifier, a Model 2610 amplifier, and a HP 3964A instrumentation recorder. A Sennheiser MKH 4161 portable microphone connected to a Panasonic Model SV-255 digital recorder (DAT) was used in the large screen cage and the field. Recorded signals were conditioned with a 12-kHz low-pass filter and then digitized at 25 kHz by a 12-bit MetraByte (Keithley/Metrabyte Inc., Taunton, MA) DAS-16G A/D board installed in a 80486 microcomputer. The digitized signal was filtered and analyzed as needed to remove background noise by DAVIS, a custom-written signal processing and spectral analysis computer program (Mankin, unpublished). Spectrum periodograms (plots of mean signal level vs. time) were generated from 4,096-point samples of a 1-min recorded segment, averaged over 10-msec increments.

Sound pressure level at the microphone was measured in units of dB (unless otherwise specified, dB//ref: 20 $\log_{10}$ [pressure in $\mu$Pa/20 $\mu$Pa] where 1 $\mu$Pa = $10^{-6}$ Pascal). The measurements were calibrated directly from the B&K Model 2610 amplifier in the anechoic chamber, or by reference to 800-Hz tones played to the Sennheiser and the B&K systems simultaneously. The frequency response sensitivity of both microphones was constant to >15 kHz. The calibration of the B&K system was checked with a B&K Model 4220 pistonphone at 250 Hz.

Sound level comparison of faint signals recorded in different environments is complicated by differences in background noise and the orientation of the microphone relative to the signal sources. The use of digital filtering enables signals in bands centered on the *Ae. taeniorhynchus* wingbeat frequency to be extracted from cricket and other background sounds. Signals from different sites then can be compared on the basis of Spectrum Level (= SPL − 10 $\log_{10}$[frequency bandwith] dB) (Beranek 1988). Spectrum Levels shown on the vertical axes in the periodograms are referenced to the frequencies specified on the horizontal axis.

Correction factors for orientation were determined in the calculation of SPLs when appropriate. The signals recorded at Rookery Bay were adjusted according to the manufacturer's calibration of dB-loss versus orientation angle. Low-frequency sounds (<500 Hz) at angles of 120° or greater are attenuated at least 10 dB relative to those at the front of the Sennheiser microphone (0°). The directionality increases with frequency. At Rookery Bay, the microphone hung a few centimeters above the water surface over a ball of pupae. (The objective was to determine if freshly emerging adults could be detected.) These recordings were corrected 12 dB to adjust for attenuation. At Brush Key and Marco Island the microphone pointed nearly horizontally about 100 cm above the surface of a shallow tidal pond. These recordings had no correction factor because the source was in front of the microphone. The recording at Flamingo was made in a black mangrove (*Avicennia nitida*) forest with the microphone pointed down about 120 cm above the ground. The Flamingo recordings had no correction factor because the mosquitoes were within about 3 cm of the microphone.

## RESULTS AND DISCUSSION

Recordings from all field locations contained brief signals with spectral peaks in frequency bands subtending the male and female *Ae. taeniorhynchus* wingbeat frequencies (Fig. 1 and Table 1), and the recordings from Rookery Bay and Brush Key contained sustained periods of signals with spectral peaks above background (MR, FB, and MB in Figs. 2 and 3). Playback of the signals through a speaker confirmed either that individual mosquitoes had passed near the microphone or that a large group of mosquitoes was flying at a distance. The swarm at Rookery Bay was still audible when the recorder was retrieved 2 h after sunset.

*Frequency analysis:* Like other mosquito species examined to date (Ogawa and Kanda 1986, Moore et al. 1986), female *Ae. taeniorhynchus* have a lower wingbeat (fundamental) frequency than males (Fig. 1 and Table 1). The frequencies are lowest just after emergence (Fig. 4). Mean wingbeat frequencies in the laboratory are com-

Table 1. Wingbeat frequencies of *Aedes taeniorhynchus* from different environments.

| Recording site | Frequency[1] ± SE (Hz) | |
|---|---|---|
| | Females | Males |
| Rookery Bay, FL | 496 ± 15d | 843 ± 18a |
| Flamingo, FL | 494 ± 21d | |
| Swarm in field screen cage | | 831 ± 8a |
| Swarm in lab holding cage | | 830 ± 6a |
| Laboratory (age 1–3 days) | | 731 ± 30b |
| Laboratory (age 4–6 days) | 441 ± 20e | 703 ± 17c |
| Brush Key, FL | 404 ± 21f | |

[1] Frequencies followed by the same letter are not significantly different by the Waller-Duncan test (SAS Institute, Inc. 1988).

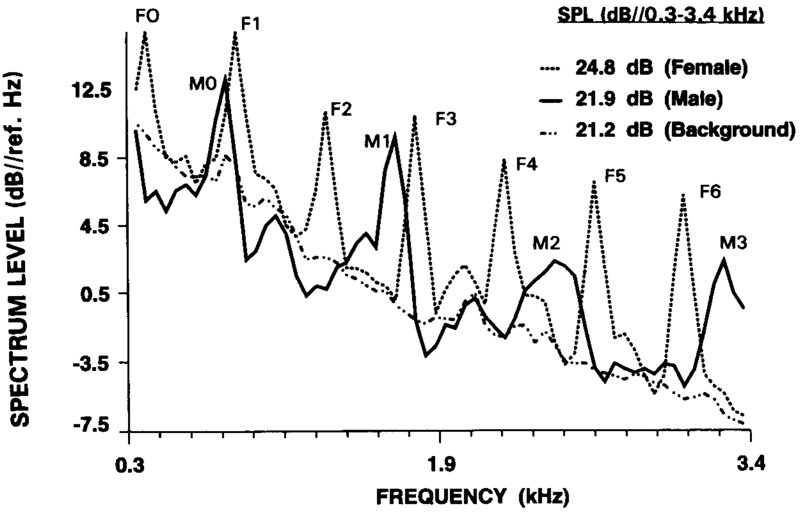


Fig. 1. Periodogram of individual male (solid line) and female (dotted line) mosquitoes in relation to typical salt-marsh background noise (dash-dot-dot line). The fundamental frequencies and harmonics are F0 = 430, F1 = 860, F2 = 1,300 Hz, . . ., for the female; M0 = 830, M1 = 1,690, M2 = 2,520 Hz, . . ., for the male. Spectrum Level is in units of dB//ref: 20 $\mu$Pa at the specified frequency (ref. Hz). SPL is in dB//ref: 20 $\mu$Pa over the range of 0.3–3.4 kHz.

pared with frequencies reported from other mosquitoes in Fig. 5. In general, the lower the weight of the mosquito, the higher the wingbeat frequency (Belton and Costello 1979).

The fundamental frequencies of the large groups of mosquitoes varied in both time and initial value. At Rookery Bay the highest intensity signal was at 875 Hz 30–40 min after sunset. The peak signal thereafter declined 75 Hz over the next 20 min, and remained at 800 Hz during the 2nd hour after sunset. At Brush Key the highest intensity signal was at 760 Hz 30–40 min after sunset. Within 20 min the peak signal had declined 80 Hz to 680 Hz. The frequencies of these signals are consistent with male *Ae. taeniorhynchus* wingbeat frequencies in Table 1. A smaller peak was present near 450 Hz (FB in Fig. 2), which reached a maximum by about 20 min

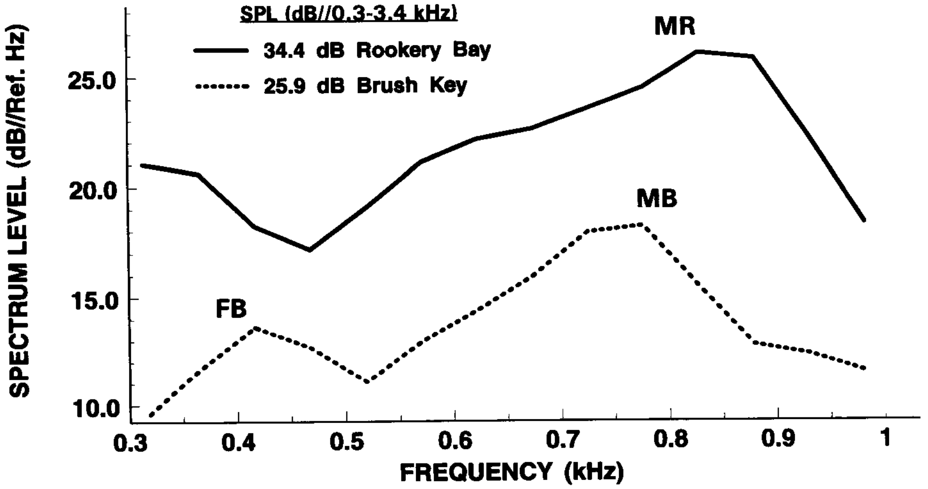


Fig. 2. Periodogram of signals recorded 23 min after sunset at Rookery Bay and Brush Key. Notation: MR, a male swarm; FB, an emergence exodus of females; MB, an emergence exodus of males and/or a swarm. Spectrum Level is in units of dB//ref: 20 $\mu$Pa at the specified frequency.

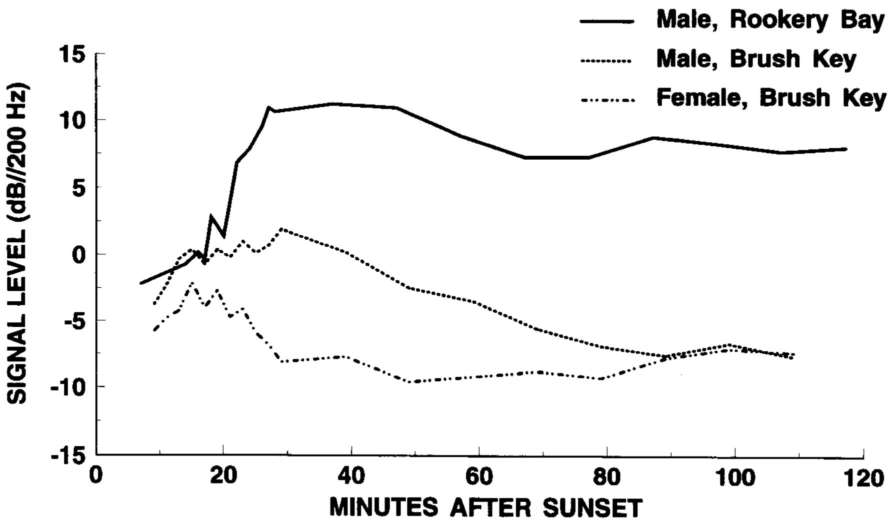


Fig. 3. Magnitude of *Aedes taeniorhynchus* wingbeat sounds recorded at Rookery Bay and Brush Key after sunset. The Spectrum Level is indicated for the specified frequency ranges (300–500, 600–800, 700–900 Hz) in units of dB//ref: 20 μPa per specified bandwidth.

after sunset. It declined to background within 10 min. This latter peak is consistent with female *Ae. taeniorhynchus* wingbeat frequencies in Table 1.

Prior reconnaissance of the Brush Key and Rookery Bay sites and previous observations of *Ae. taeniorhynchus* behavior (Haeger 1960) suggest that the 2 recordings detected qualitatively different events. Because no females were detected at Rookery Bay, the signals detected at MR in Fig. 2 probably came from a large male swarm. The peak emergence had occurred one day previously. Both sexes were detected in signals at Brush Key. The male peak, MB, was louder and lasted longer than the female peak, FB. Perhaps this event began as an emergence exodus of both sexes and continued as a male swarm.

*Sound pressure levels:* The signals were louder at Rookery Bay than at Brush Key (35 vs. 26 dB maximum SPL between 0.3 and 3.4 kHz) and 12 dB//ref: 700–900 Hz vs. 1 dB//ref: 600–800 Hz Spectrum Levels (Fig. 3). They were audible at both locations but could not be localized precisely because of their large size. The near edges of the swarms probably were within 10 m, and the centers within 50 m of the microphone. The

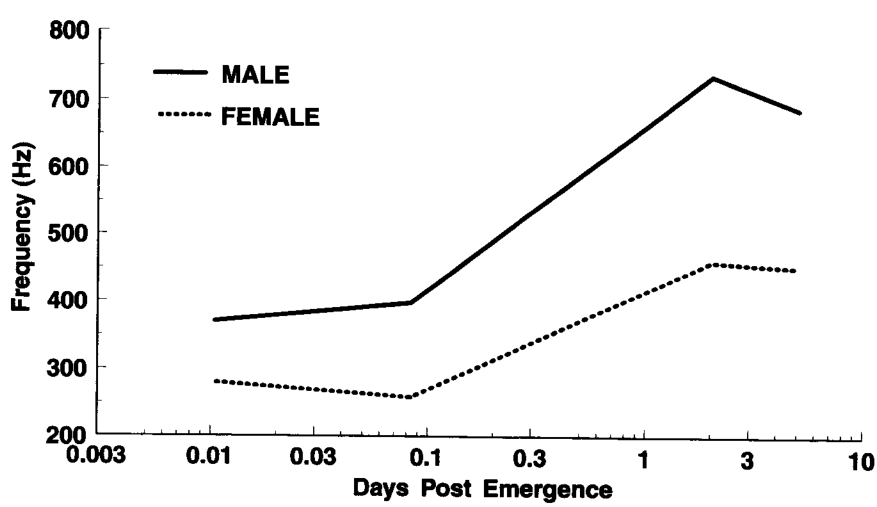


Fig. 4. Average wingbeat frequencies of *Aedes taeniorhynchus* at different times after emergence.

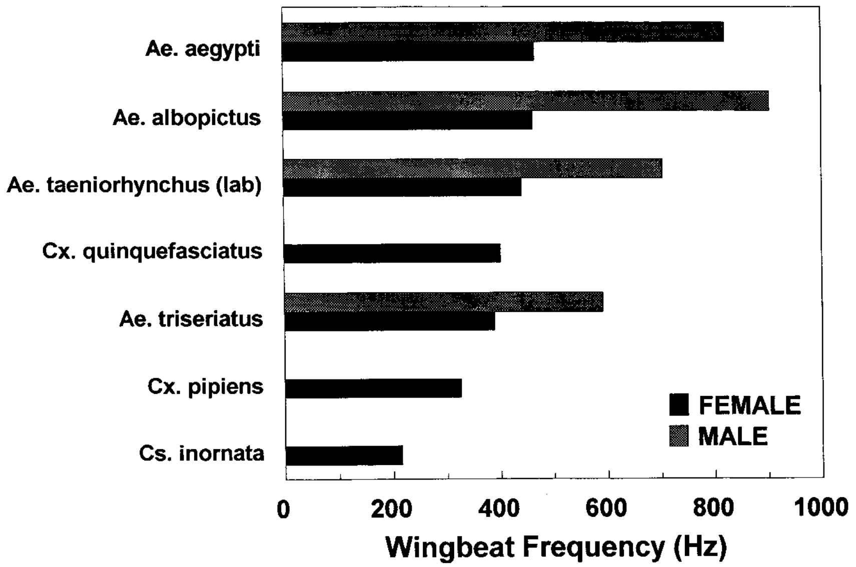


Fig. 5. Comparison of average wingbeat frequencies of different mosquito species. References: *Culex pipiens* and *Culiseta inornata,* Belton and Costello (1979); *Aedes triseriatus,* Moore et al. (1986); *Aedes aegypti* and *Aedes albopictus,* Ikeshoji (1981); *Culex quinquefasciatus,* Ikeshoji et al. (1987).

sound of the mosquito swarms contributes negligibly to the total environmental background except at the fundamental wingbeat frequency and the first 2 harmonics (Figs. 1 and 6). The signal is sufficiently above background at these frequencies to devise a simple filtering system that automatically detects a swarm's presence. The filtering is necessary because high-intensity signals (probably from the *Cytoxipha* green bush cricket) appear at 6 kHz. The other peaks in the background spectrum of Fig. 6 are sounds of cicadas (2.5 kHz) and crickets (4.2 and 8 kHz).

The beginning of above-threshold signals of male *Ae. taeniorhynchus* wingbeats at Brush Key coincided with the beginning of a low-intensity signal at the female wingbeat frequency (FB in

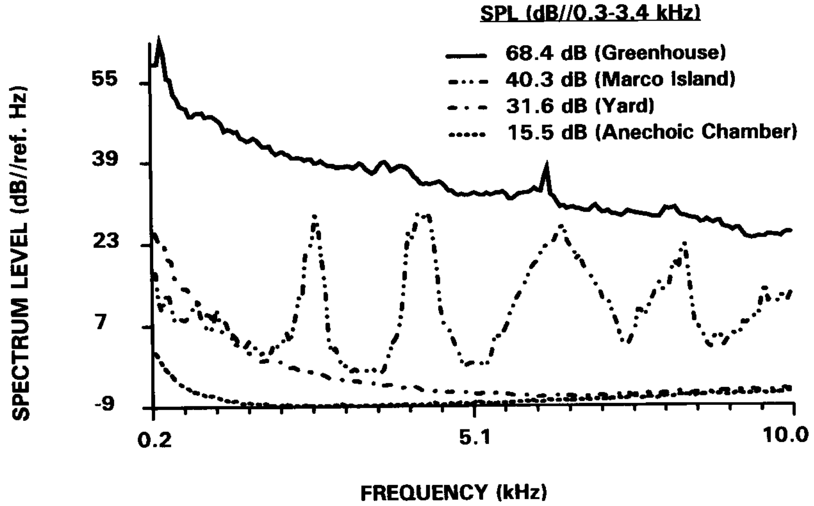


Fig. 6. Comparison of Sound Pressure Level (SPL) in quiet and noisy environments. Backgrounds at Rookery Bay, Flamingo, and Brush Key were similar to that shown for Marco Island. SPL is in units of dB//ref: 20 $\mu$Pa over 0–12.5 kHz. Spectrum Level is in units of dB//ref: 20 $\mu$Pa at the specified frequency (ref. Hz).

Fig. 2). The Spectrum Level reached only to −4 dB/ /300–500 Hz, undetectable to the unaided ear but above the background noise Spectrum Level of −8 dB/ /300–500 Hz (Fig. 3). The timing of the signals at the male and female wingbeat frequencies is consistent with a hypothesis that the event was an emergence exodus.

Because large swarms of mosquitoes are relatively rare, the most practical surveillance technique is one that detects individuals, not just swarms. However, individual *Ae. taeniorhynchus* males and females have low SPLs, 22–25 dB/ /0.3–3.4 kHz at a 3-cm distance from the microphone (Fig. 1). These are similar to levels measured by Belton and Costello (1979) for *Culex pipiens* Linn. and slightly below Jones's (1964) measurements of *Anopheles gambiae* Giles. A surveillance device based on the sounds of individual mosquitoes probably would require an attractant source to bring mosquitoes close enough to raise the SPL above the 22-dB saltmarsh acoustical background.

*Technical requirements for a practical acoustical detection device:* The measurements above indicate that *Ae. taeniorhynchus* flights are loud enough above background in remote areas to be detected by modern acoustical technology. Individual mosquitoes can be identified in such an environment if they are attracted to the microphone. Swarms are easily detectable from > 10 m.

The question whether an acoustical surveillance system is practical thus reduces to an analysis of cost versus benefits. A battery-powered system that identifies 25–35-dB acoustical signals between 0.5 and 1 kHz can be developed relatively inexpensively, particularly if the data are stored on site or transmitted over distances less than 500 m (e.g., Ke and Killick-Kendrick 1992). Greater expense is involved in transmitting signals automatically to a distant monitoring center. The net benefit is greater if the mosquito detector is installed at an environmental monitoring station already equipped with telemetry.

## ACKNOWLEDGMENTS

F. Van Essen and G. Lemire, Collier Mosquito Control District, and R. Derrow and T. Forrest, National Center for Physical Acoustics, gave helpful advice. I thank D. Kline, ARS Medical and Veterinary Research Laboratory, who asked the initial questions that led to this study and provided encouragement. At the Insect Attractants, Behavior, and Basic Biology Laboratory, G. Posey assisted with graphics and E. Foreman assisted with acoustical signal acquisition and analysis. I give very special thanks to S. Ritchie, Collier Mosquito Control District, and D. Addison, The Conservancy, Inc., who located mosquito emergences, accompanied E. Foreman and me to the recording sites, and provided helpful discussions.

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