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An Index for Assessing the Foraging Activities of Honeybees with a Doppler Sensor

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***Abstract*— Most pollination of commercial blueberries is carried out by honeybees from hundreds of hives. An activity sensor for monitoring the health and productivity of beehives is presented. Honeybees flying near the entrance of a beehive were observed with a low-powered 5.8 GHz Doppler radar. Spectral moments, entropy, diversity, and root-mean-square (rms) power were evaluated to identify foraging bees and to quantify the level of foraging activity.**

Theoretical and experimental results are presented to demonstrate that entropy, diversity, and rms power are correlated and are equally valid indicators of bee activity. In particular, the rms power of the Doppler signal can be measured without a coherent receiver and without signal processing. This type of measurement lends itself to a second, considerably less expensive, implementation of a bee activity sensor.

Keywords–Doppler radar; spectral entropy; foraging honeybees

I. INTRODUCTION

Honeybees are not only a source of honey, but they also act as important ecological and commercial pollinators [1], [2]. An experienced beekeeper can assess the productivity and health of a bee colony by watching foraging bees entering and leaving the hive and by listening to the sounds coming from the hive [3]. However, this assessment is quite subjective. A formal inspection usually requires opening up the hive, which can become very time-consuming. More than 500 beehives may have to be checked on a 100-acre blueberry farm. Since it is impractical to inspect that many hives manually, an automated monitoring system is of interest.

In this paper a metric and sensor are proposed that attempt to quantify the above observations by a beekeeper. In Section II, sensor options will be considered. The best metric will be derived in Section III. A baseline sensor and experimental results will be presented in Section IV and V. An inexpensive implementation of the sensor and its validation will be presented in Section VI.

II. SENSOR OPTIONS

A. Acoustic Sensors

Several patents have been granted for determining the health of a hive by analyzing bee sounds [4]-[6]. Systems for automatically reporting the average sound level inside a hive have been developed [7]-[9]. All of these systems require inserting a microphone into the beehive which is disruptive to the colony. Acoustic signals external to a hive are too often corrupted by environmental noise.

B. Optical Sensors

Other honeybee monitoring systems [10], [11] use photoelectric counters to collect bee traffic data at the entrance to the hive. Such counters, however, may report erroneously high levels of foraging activity when the bees are actually just milling around the entrance. Video surveillance methods have been considered to count and classify bees at the hive entrance [12], [13]. They require sophisticated image processing. Infrared imaging of beehives is limited by background radiation.

C. Doppler Motion Sensor

Passive infrared sensors are commonly used for motion detection. These are threshold detectors, e. g., when motion is detected a light is turned on. A Doppler radar can not only detect motion, but more importantly, it can also quantify the level of activity.

In a typical, high-powered Doppler weather radar, insect detections are considered a nuisance [14], [15]. However, these very detections can be exploited for entomological research. For example, a low-powered Doppler radar has been able to detect vibrations coming from bees inside a beehive [16]. In this paper, a similar radar will be used to observe bees flying outside the hive.

Bee foraging activity will be deduced from Doppler spectra. The top flying speed of bees has been reported to be about 15 mph [17]. If the sensor operates at a frequency of 5.8 GHz, Doppler frequencies between ± 260 Hz can be expected. This is well within the frequency response of digital audio recorders. No significant interference has been observed from bee wings beating at 250 Hz.

Since many Doppler spectra need to be examined, a single parameter describing each spectrum is desirable. The mean Doppler frequency, the Doppler frequency spread, the entropy, the diversity, and the root-mean-square power of the Doppler radar signal have been considered. All of these indices are shown to be correlated, and equally valid indicators of bee activity.

The above conclusion will be experimentally verified with a coherent Doppler radar. Since rms power measurements

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require the least computational effort, the conclusion will be confirmed with a considerably simpler noncoherent bee activity sensor containing a logarithmic square-law detector.

III. BEE ACTIVITY INDICES

The concept for measuring bee activity with a Doppler sensor is based on the following observations: At times, bees appear to be just randomly flying about the hive entrance. At other times, foraging bees launch themselves quite purposefully from the hive entrance and rapidly accelerate along a straight path to a traveling speed of about 10 mph. When bees are observed by a Doppler sensor, a uniform, noise-like Doppler spectrum would be expected in the former case and a much narrower Doppler frequency response in the latter case. The power in the spectrum would be an indicator of the level of flying activity.

A comparative lack of flying activity or frenzied flying activity would indicate that the colony has a problem, requiring intervention by the beekeeper.

The different metrics for quantifying the Doppler spectra will now be considered.

A. Doppler Moments

In a weather radar, precipitation spectra are typically characterized by their spectral moments [18]. Let $\{S(n)\}$ denote the power spectral densities (PSD) at discrete frequency $\{f(n)\}$, $n = 1, 2, \ldots, N$. The average Doppler frequency is then given by

$$\langle f \rangle = \frac{\sum f(n)\ S(n)}{\mathrm{P}} \tag{1}$$

where $\mathrm{P} = \sum S(n)$ is the power in the spectrum. The spectral variance is defined by the second moment

$$\sigma^2 = \frac{\sum (f(n) - \langle f \rangle)^2 S(n)}{\mathrm{P}} \tag{2}$$

and the spectral width by 2σ.

B. Entropy and Diversity

"Entropy" is an intriguing index for characterizing the apparently random flight patterns of bees. Entropy has been used, almost synonymously with diversity, as a measure of either homogeneity and order, or randomness and disorder [19]. It has been applied to communications [20], agriculture [21], biology [22], ecology, medicine and even music. It has also been used to detect moving targets with a Doppler radar [23]. Most often, the formula for "information entropy" introduced by Shannon [20] is applied

$$\mathrm{H} = -\sum p(n) \log p(n) \tag{3}$$

where $\{p(n)\}$ is a probability density function (PDF). By definition, $p(n) \geq 0$ and $\sum p(n) = 1$.

We will not attempt to link our use of the term "entropy" to the concept of entropy in thermodynamics [24]. Instead we consider (3) as a weighted geometric mean of the PDF

$$\mathrm{H} = 1 / \prod p(n)^{p(n)}. \tag{4}$$

Unfortunately, if one value of the PDF is zero, (4) becomes meaningless [25].

A more generalized measure of entropy can be defined by a weighted arithmetic mean of the PDF [19]

$${}^{q}\mathrm{D} = [\sum p(n)^q]^{1/(1-q)} \tag{5}$$

where q is the diversity order. When $q = 2$, (5) is referred to as Simpson's diversity [26]. For a uniform PDF it is easy to show that

$$\log({}^{2}\mathrm{D}) = -\mathrm{H}. \tag{6}$$

For other probability density functions (6) is approximately valid. Evidently, Simpson's diversity and Shannon's entropy are related.

C. RMS Power

Determination of a Doppler spectrum starts with a set of temporal radar observations $\{x(n)\}$, $n = 1, 2, \ldots, N$. The root-mean-square power in the observations is

$$\mathrm{P} = \frac{1}{N} \sum |x(n)|^2 . \tag{7}$$

By Parseval's theorem [27] the power in a function is the same as the power in its Fourier transform, that is

$$\mathrm{P} = \frac{1}{N^2} \sum |X(n)|^2 = \sum S(n) \tag{8}$$

where $\{X(n)\}$, $n = 1, 2, \ldots, N$ are the components of a Discrete Fourier Transform (DFT) of $\{x(n)\}$. A formally equivalent probability density $p(n)$ is defined by the normalized power spectral density

$$p(n) = S(n)/\mathrm{P}. \tag{9}$$

Substituting (9) into (5) with $q = 2$ yields

$$\log({}^{2}\mathrm{D}) = 2 \log(\mathrm{P}) - \log \left[\sum S^2(n) \right]. \tag{10}$$

Thus, (10) relates the root-mean-square power in the observations to diversity, which in turn is related by (6) to entropy.

Experiments will now be carried out to verify that entropy and diversity can be derived from the rms power in the observations without calculating a Doppler spectrum. The power could be measured directly with a true rms reading analog voltmeter.

IV. DOPPLER SENSOR

A Doppler radar for detecting the sound and vibrations from stationary bees inside a beehive was described in [16]. In contrast to the radar in [16], the radar in Fig. 1 observed flying bees outside the beehive, measuring their speed as a positive or negative Doppler frequency shift. As such, it required in-phase and quadrature (I/Q) receiver channels which are more expensive, but necessary to establish a Doppler performance baseline and to prove the above metric relations. The sensor operated in the unlicensed 5.8 GHz Industrial, Scientific and Medical (ISM) band with a effective radiated power of 18 dBm. This power level was sufficient to detect individual bees at a distance of six feet.

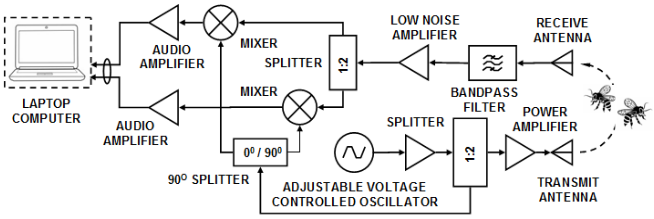

Fig. 1. Bee Doppler sensor (Version I)

The output of the Doppler sensor is a dual-channel audio signal that was recorded in 9-sec blocks with a laptop computer. Each block was stored as a *.wav file consisting of 16-bit in-phase and quadrature data sampled at 8,000 samples/second.

A. Sensor Calibration

An unambiguous resolution of positive and negative Doppler frequencies requires that the I/Q data are in perfect quadrature. Numerous techniques have been proposed to correct for the I/Q channel imbalance [28]. Since the sensor is unlikely to observe bees with exactly equal and opposite Doppler frequencies at the same time, the correction is particularly simple: A rotation is applied to the I/Q data that minimizes the off-diagonal terms in their covariance matrix while preserving the total power. An example of an uncalibrated and calibrated I/Q data block is shown in Fig. 2.

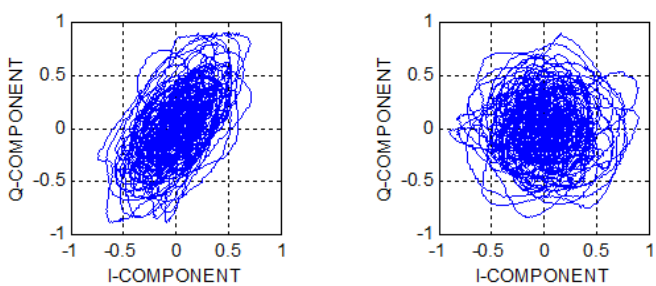

Fig. 2. Uncalibrated and calibrated I/Q data

B. Signal Processing

The analysis of the bee sensor data is based on Doppler-Time-Intensity (DTI) plots obtained by correcting each 9-sec block (72,000 complex samples) for I/Q imbalance and by applying Short Time Fourier Transforms (STFT). I.e., each block is broken up into 0.125 sec (1000 samples) frames overlapping by 0.05 sec (400 samples). A Hamming window is applied to each frame, an FFT is taken, and the results are plotted in dB. Each DTI is then time-averaged and reduced to a single metric by calculating (1), (2), (3), (5) and (7).

V. EXPERIMENTAL RESULTS

The relative location of the sensor antennas and beehive entrance are shown in Fig. 3. Examples of typical DTI plots collected over the course of a day are shown in Fig. 4. The unique Doppler signatures of individual bees flying out (Fig. 4a) and flying back (Fig. 4c), are clearly evident. There is a lot of Doppler activity in the afternoon (Fig. 4b) and very little at night (Fig. 4d). The corresponding time-averaged Doppler spectra are shown in Fig. 5. All bee activity indices were derived from such data.

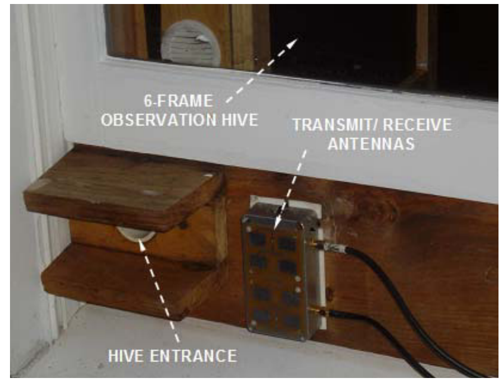

Fig. 3. Beehive and sensor antennas

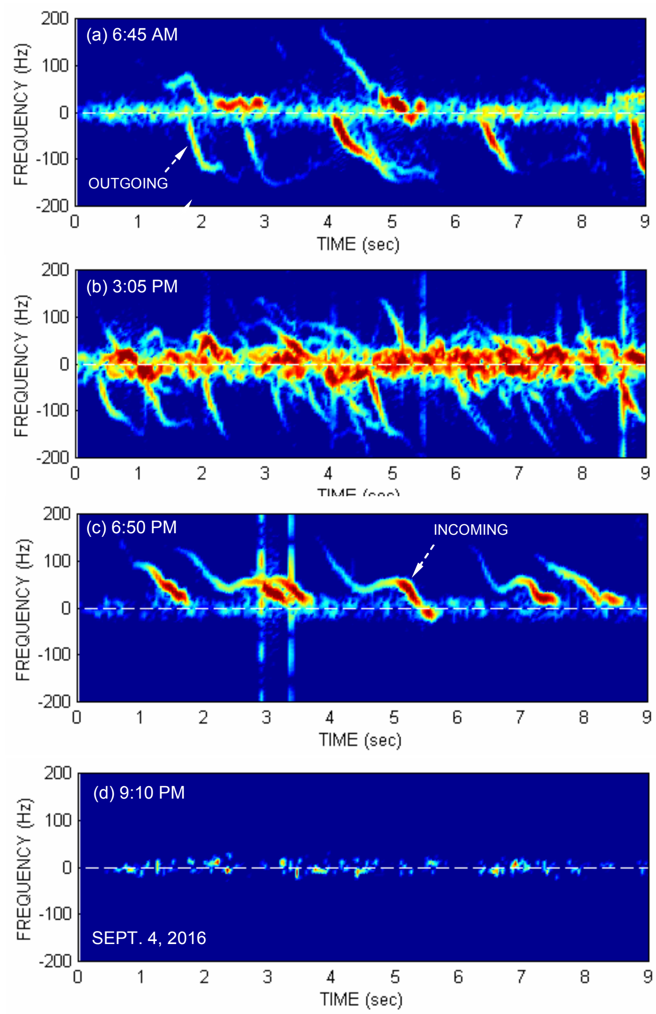

Fig. 4. Typical DTI plots

The mean Doppler frequency and spectral width recorded over a 24-hour period are shown in Fig. 6. The mean Doppler frequency is negative in the morning (departing forager bees) and positive in the evening (returning forager bees). Bees seem to get a late start in the morning and all come home by sunset. Between sunrise and sunset the spectral width becomes considerably narrower.

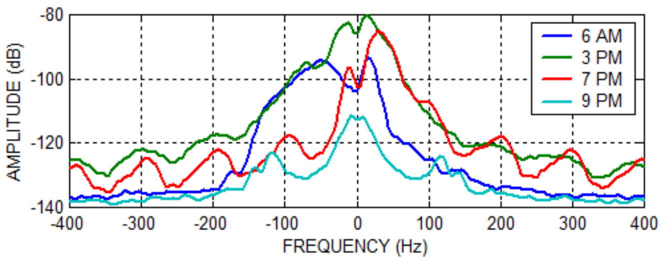

Fig. 5. Corresponding time-average Doppler spectra

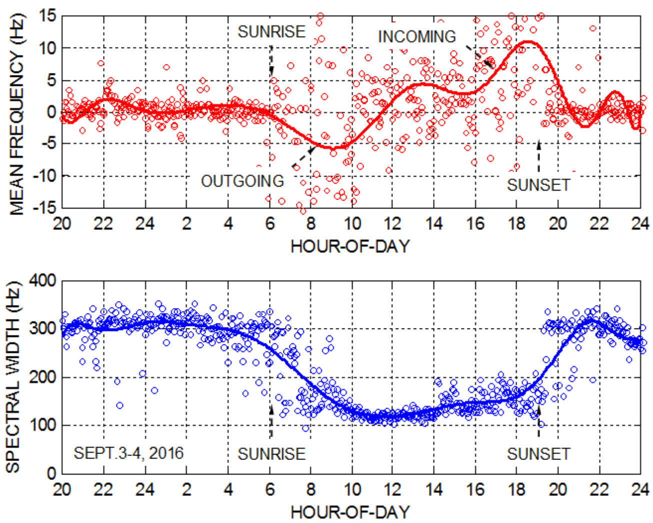

Fig. 6. Mean Doppler spectrum frequency and width

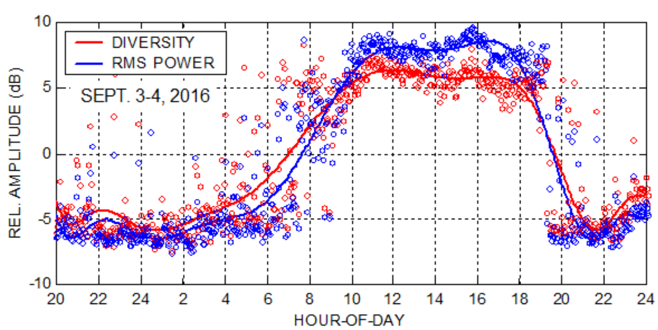

Fig. 7. Temporal variation of diversity and rms power

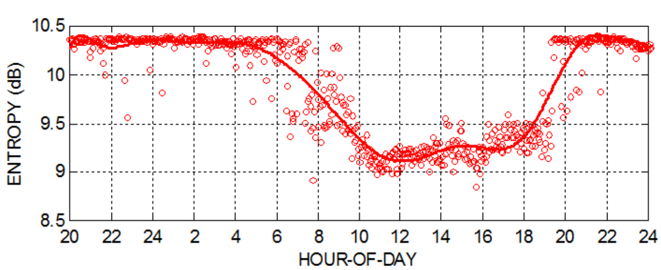

Fig. 8. Temporal variation of entropy

The entropy, diversity and rms power were also calculated for the same 24-hour period. As predicted by (10), Fig. 7 illustrates that the temporal behavior of diversity and rms power are substantially the same. Similarly, the spectral width in Fig. 6 and the entropy in Fig. 8 appear to be correlated. The high correlation coefficients in Table 1 prove that spectral width, entropy and diversity are highly correlated with the rms power. This means that those indices could be deduced from the rms power in the Doppler signal without coherent receiver channels, without receiver calibrations or a great deal of signal processing.

Table 1.

Correlation between bee activity indices

	Correlation with RMS power
Spectral Width	-0.97
Entropy	-0.99
Diversity	0.98

VI. Bee Activity Sensor Implementation

The I/Q channels will not be required in the final bee activity sensor (Version II). The above result suggests a considerable simplification of the bee activity sensor by replacing the coherent heterodyne receiver with a logarithmic square-law detector [29]. This detector was originally intended to detect bee vibrations and cannot distinguish between incoming and outgoing Doppler. However, in the absence of vibrations, the DC voltage of such a detector is proportional to the logarithm of the Doppler signal power, exactly as required by (10).

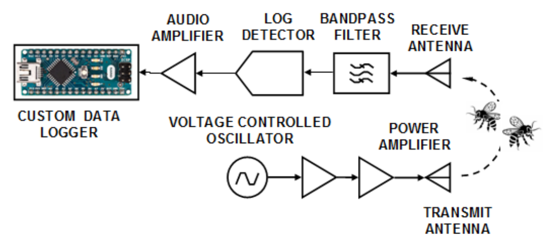

Fig. 9. Bee Doppler sensor (Version II)

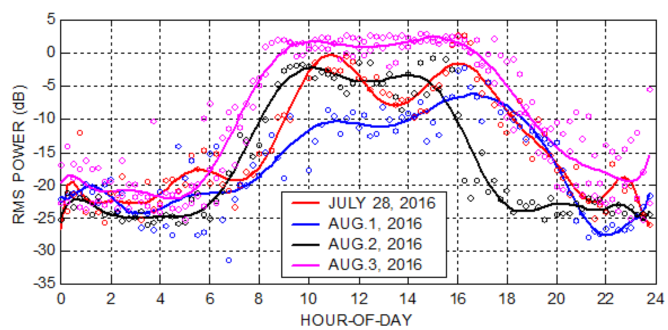

Fig. 10. RMS power measured by bee sensor (Version II)

A block diagram of the simplified bee activity sensor (Version II), which also operated at 5.8 GHz, is shown in Fig. 9. The audio frequency output of that system was digitized with a 10-bit A/D converter at 8000 samples/sec on an Arduino Nano board. The rms power was calculated and averaged over one minute every 15 minutes for several days. The observations in Fig. 10 are substantially similar to those obtained with the original Doppler sensor in Fig. 7. During that time, the weather was uniformly sunny, with lows of 50^{o}F at night and highs of 80^{o}F during the day. Further studies will be required to explain differences in the daily observations.

VII. CONCLUSIONS

A low-powered Doppler radar operating at 5.8 GHz was shown to be capable of detecting flights of individual honey bees. Conventional signal processing techniques were applied to calculate mean frequency, spectral width, entropy, diversity, and rms power of the Doppler spectrum. Bee activity information obtained from spectral width, entropy, or diversity calculations was substantially the same as that obtained with considerably less effort from the rms power measurements. This result led to the construction of an inexpensive bee activity sensor based on the rms power in the Doppler signal.

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