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A novel non-invasive radar to monitor honey bee colony health

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ABSTRACT

Honey bees are of vital importance to global crop production. Colony losses have reached historic levels in Europe and North America and are high in other parts of the world. The decline in honey bee health has resulted in the demand for novel mechanisms of monitoring colony health by beekeepers and researchers. Methods of monitoring bee health traditionally involve opening of the hive either for manual data collection or the use of invasive electronic monitors. This study evaluates a beehive activity monitor based on the Doppler radar principle as a tool for assessing honey bee colony health. The research was conducted during a two-year study (2017–2018). We discuss the development of a portable Doppler radar unit and three experiments conducted with the aim of showing its utility in monitoring colony health. First we determined the relationship between: (I) forager activity and colony health ($r^2 = 0.433$, $P = 0.006$), (II) Doppler unit root mean square (RMS) and forager activity ($r^2 = 0.766$, $P = 0.013$), and then (III) Doppler unit RMS and colony health measured as total sum of brood and worker population ($r^2 = 0.731$, $P = 0.026$). This small portable Doppler unit is solar powered and can be deployed in any apiary to provide beekeepers with a tool for tracking their colonies' health in real time.

1. Introduction

Animal pollinators are keystone species (Bond, 1994). It is estimated that 90 percent of all wild flowering plants depend on animal pollination (Garibaldi et al., 2016) and that over the past 50 years, the utilization of animal pollinators has increased agricultural yield by 300% (Garibaldi et al., 2016). Of these pollinators, honey bees are vital for high levels of crop production in much of the developed world (Allen-Wardell et al., 1998). This is particularly important in light of a growing global population of approximately 83 million people per year (World Population Prospects: The 2017 Revision, 2017). Bees and other animal pollinators contribute to the production of about one-third our food, especially fruits and nuts, but also seed production of many vegetable species (vanEngelsdorp and Meixner, 2010; Sass, 2011; Berenbaum, 2018). Pollination from managed honey bees, wild and managed bumble bees, and managed and wild leafcutting and mason bees account for a variety of harvested fruits, vegetables, nuts, and forage; such as: alfalfa, almonds, apples, apricots, blueberries, cantaloupe, cashews, cherries, clovers, cucumbers, okra, pumpkins, raspberries, strawberries, and tomatoes (Delaplane et al., 2000). Almonds are almost exclusively pollinated by honey bees and therefore, almost completely dependent upon them (Ghazoul, 2015).

Unfortunately, honey bee populations (total colonies) have been decreasing across the world, particularly in the United States, China, Japan, France, Belgium, Switzerland, Germany, the United Kingdom, the Netherlands, Italy and Spain (Kluser et al., 2010). United States' managed honey bee populations suffered 40.1% loss between the survey period of 2008–2018 (vanEngelsdorp et al., 2009; Jacques et al., 2017; Bruckner et al., 2018), while other countries such as the UK show more drastic colony losses, losing approximately 54% of commercial honey bee populations since 2010 (Potts et al., 2010). This decline in honey bee populations is thought to be due to a phenomenon known as Colony Collapse Disorder (CCD) (Cox-Foster et al., 2007). The cause for CCD has been officially defined by environmental and biological scientists as not one specific cause, but the simultaneous accumulation of several stressors that affect colony health such as: climate change, pesticide exposure, loss of natural habitat, viruses, fungal pathogens, and arthropod parasites such as *Varroa* and tracheal mites (Besson, 2016; Ostiguy et al., 2019).

It is therefore imperative that beekeepers be able to monitor the health of their colonies. The most common technique used by beekeepers to examine colony health is to manually open the hives and

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observe the colony for signs of health or illness; such as worker bee population size, queen supersedure cells, queen activity and egg laying, presence of brood, disease, parasites and seasonal honey production (Drummond et al., 2012). This method, although allowing a comprehensive assessment of a colony's health, is time consuming and expensive as it requires the beekeeper to manually go through each and every frame within every hive sampled. This is also an invasive procedure that decreases the colony's overall productivity for several days after inspection (Simone-Finstrom et al., 2016).

Many different sensors for monitoring honey bee activity or colony strength have been developed over the past two and a half decades (Struye et al., 1994; Mezquida and Martinez, 2009; Shaw et al., 2011; Meikle and Host, 2015; Chen et al., 2015; Kale et al., 2015). Several of these sensors have been patented (Woods and Wood, 1957; Bromenshenk et al., 2007; Brundage, 2012) and are commercially produced and sold, by companies such as *Arnia*® and *Bee Smart Technologies*®. These devices include technologies that measures various conditions within the hive such as: internal air temperature, humidity, acoustics and weight change (honey production and colony size). Through monitoring many conditions associated with colony health beekeepers can be more informed about the state of their colonies (Pettis and Delaplane, 2010). Nevertheless, these sensors involve opening up and even deconstructing hives for installation. *Solutionbee's B-ware*® and *Hivemind*® require a scale to be placed under each hive for honey production measurements. *Arnia*® produces a monitoring device that measures audio levels, humidity and temperature of the internal hive state, requires continuous maintenance as bees will entomb the perceived invasive sensors with propolis (bee collected resin). The set-up time and further maintenance of the invasive wiring are impractical for beekeeping industries with thousands of hives, and too expensive for the local beekeeper. It is evident that there is a need for research into simpler, less invasive and less expensive technology to assess colony health.

One possibility is to look towards the hive entrance rather than internal factors of the hive. There is evidence that activity of bees coming and going from the hive are a direct measure of colony health (Storch, 1985). The "front of a hive," also known as the entrance, is a location where complex interactions between honey bees and their environment occur. The activity seen at the front of the hive can be broken down into two main categories: general activity and foraging activity. General activity at the front of the hive includes young worker bees orienting themselves with their environment at ca. 20 days of age (Capaldi and Dyer, 1999), guard bees protecting the colony from other invading honey bees, and honey bees fanning at the front of the hive during hot days in order to regulate internal colony temperatures or produce evaporative dehydration of nectar (Storch, 1985). The decrease in this general activity is known to be a sign of a weakening or a distressed colony, and the decline in young honey bee orientation flights is a sign of a decrease in the future labor force (foraging workers) for the hive. The second category of activity is foraging. These are the bees that go in and out of the hive to collect nectar and pollen for the raising of immature bees and the production of honey for the colony. Often, honey stores are used to determine colony productivity and therefore health of the colony (Khoury et al., 2013). However, by continuously monitoring activity of honey bees responsible for that productivity, one can estimate the health of the hive.

Previous attempts to measure hive entrance activity have included the use of acoustic and optical sensors (Patent No. US 2007/0224914 A1, 2007; Bromenshenk, 2007; Babic et al., 2016). Acoustic signals external to a hive are too often corrupted by environmental noise. An example of an optical sensor is *Eyes on Hives*® which is a camera-based system coded with an algorithm to track honeybee flight activity and allows virtual observation from any room of one's home, but is costly. Another example of an optical sensor is *BeeScan*® which uses photoelectric counters embedded in tunnels in a device that needs to be installed at the beehive entrance. These photoelectric counters are used to collect incoming and outgoing bee traffic data. The problems arising with this type of sensor are that it once again requires: a) deconstructing the hive for initial installation and b) cleaning daily as pollen and oils carried or secreted by bees coat the sensor causing a decline in the sensor's efficiency (Struye, 2001; Drummond, pers. obs.). It is impractical and tedious to clean the 32 entrance tunnels per hive daily; especially for beekeepers with hundreds to thousands of hives. Therefore, neither sensor type is an ideal device for commercial use, however, they are useful for honey bee research studies (Struye, 2001).

The question then becomes, "How can one produce a sensor which measures bee activity at the hive entrance that is non-invasive and allows quantification of honey bee colony health?" One solution is a technology that is widely used: Doppler radar. The Doppler effect is defined as a change in frequency or wavelength of a wave reflected from a moving target and measured by a stationary observer (Giordano, 2009). The wave can be acoustic or electromagnetic, such as radio frequency or light waves. Doppler radar technology utilizes electromagnetic waves to detect a moving object and measuring its speed, such as a car traveling down a road (as in the commercially available Doppler sensor, HB-100®). Bees can also be tracked by Doppler sensors (Chen et al., 2006; Aumann and Emanetoglu, 2016a).

A Doppler radar sensor can be used to measure the speed of individual bees and determine if they are flying away from or towards the beehive, as the Doppler frequency shift is proportional to the bees' speed (Aumann and Emanetoglu, 2016b; Aumann et al., 2017). This is practical when only a few bees fly in or out of the hive in a one second period, but becomes more difficult as the number of moving bees per unit time increases. An alternative application of the Doppler radar focuses on total bee colony activity as measured by the total return signal strength, instead of the "identify and track individuals" method. The advantage of this approach is that the total energy in the return signal is proportional to the number of bees flying in and out of the hive, which significantly simplifies the data sampling and processing requirements for the bee hive monitor. It also produces a signal value that a beekeeper may use to evaluate the health of their colonies (Aumann et al., 2017).

This study addressed the development of a portable hive mounted Doppler radar device that measures honey bee colony activity at the hive entrance. We conducted measurements on standard Langstroth hives, housing colonies of various population sizes. Over the course of two-years we built and tested several prototypes of our Doppler unit. We conducted three experiments with the following objectives: 1) compare colony activity using visual quantification and measurements of activity derived from Doppler radar, 2) evaluate brood and adult population size as a measure of colony forager activity at the hive entrance, and 3) assess colony population size using Doppler radar measurements of honey bee activity at the hive entrance as a predictor of colony health.

2. Methods

2.1. Design of the portable Doppler unit

The beehive activity monitor consisted of a Doppler radar, a signal conditioning amplifier, a microcontroller for data acquisition and processing, a real-time clock for time stamping the data, a micro SD card for data storage, and a power management block. Fig. 1 shows the functional breakdown of the hive activity monitor.

The beehive activity monitor was based on measuring flight activity levels as determined by the total energy at the low-frequency output of a Doppler radar (Aumann et al., 2017). Preliminary measurements using Doppler radars operating at 5.8 GHz and 10.5 GHz indicated that foraging bees fly out of the hive entrance with a constant acceleration between 0.4 g and 0.8 g, resulting in a velocity (v_{bee}) ranging between 2 m/s and 3 m/s at a range of 1 m. For bees returning with pollen, the additional weight of the pollen resulted in a slower speed and

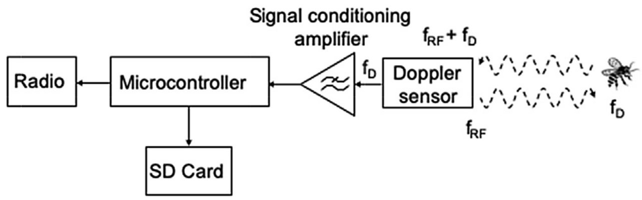

Fig. 1. Functional breakdown of the beehive monitoring device (f_D = Doppler frequency, f_{RF} = radar frequency).

deceleration.

The Doppler frequency f_D is dependent on the bee velocity v_{bee} and the radar frequency f_{RF} as depicted in Eq. (1):

$$f_D = \frac{2v_{bee}}{c} f_{RF} \tag{1}$$

where c is the speed of light.

Two factors influenced the choice of radar frequency: (i) bee size, and (ii) availability of low-cost Doppler sensors in the ISM (Industrial Scientific Measurement) babds. Three possible choices were 5.8 GHz, 10.5 GHz, and 24 GHz. At higher frequency, bee size becomes more comparable to radar wavelength, resulting in a radar frequency to the 4th power enhancement of radar cross section. Operating at 24 GHz would have been optimal, but the walls of weather-proof Doppler unit boxes were expected to cause significant signal attenuation. Therefore, the radar frequency of 10.5 GHz was chosen for the beehive activity monitor. At 10.5 GHz, the expected Doppler frequencies range from 140 Hz to 210 Hz for an outbound foraging bee one meter away from the beehive. The HB-100®, which is a 10.5 GHz Doppler radar-based motion detector, was chosen as the sensor.

The commercially available HB-100® sensor is designed for detecting human movement and for automotive collision avoidance systems. As a honey bee has a cross-section a thousand times smaller than a human (Riley, 1985), the signal needed to be amplified and filtered. A fifth order active bandpass filter was designed for signal conditioning. The amplifier was designed with a peak gain of 4000 V/V (72 dB) at a frequency of 300 Hz, and a 60 dB/dec roll off for the upper frequencies. The lower frequency poles were placed at 5 Hz and 50 Hz. This underweighted the return signals from slow moving bees (< 0.7 m/s) compared to the signals from faster moving bees. Slower moving bees would be closer to the beehive entrance, resulting in a larger radar return signal compared to faster moving bees that would be further away from the hive entrance. The filter characteristics were thus distorted to give larger weight to the return signal from faster moving bees.

The microcontroller (32-bit ATSAMD21G18® on an Adafruit Feather board®) had several functions. It "woke up" the Doppler sensor for 30 s every five minutes to perform a bee forager activity measurement; digitized the raw data using its onboard 12-bit analog-to-digital converter (ADC); calculated the root-mean-square (RMS) of the AC signal over a 30 s period to derive the colony activity index; and saved the time-stamped data to a microSD card, along with diagnostic information including battery voltage and the monitor's own internal temperature. The real-time clock and microSD card reader were on an Adafruit AdaLogger Feather Wing®.

The power management block consisted of a 3.7 V 2000 mAh lithium polymer battery, an Adafruit PowerBoost 500 battery charger, and a 1 W solar panel. The PowerBoost 500 also up-converted the battery voltage to +5 V which was needed for proper operation of the HB-100 Doppler sensor®. The estimated daily energy consumption of the monitor was 2 Wh. With an average solar insolation of 5 peak sun hours and a minimum solar insolation of 3.8 peak sun hours between April and October in Maine at 45° N latitude, a 1 W solar panel was chosen to ensure the battery would be sufficiently charged even with cloudy or rainy conditions.

Fig. 2. A Prototype 3 bee hive monitor unit is located just above the hive entrance. The base station is nearby, in a yellow weatherproof container. The two were powered by separate solar panels, one on top of the hive for the Doppler unit and for the adjacent base station. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Three different types of bee hive monitor prototypes were built and tested for the summer 2017 field season. A single Prototype 0 unit was constructed using an HB-100®, an audio amplifier, a battery and a digital audio recorder. This unit was used to record the raw Doppler data for analysis. The single Prototype 1 unit was functionally similar to the unit described above, except that it used an Arduino Nano® and operated using a +5 V supply. The Prototype 2 design used the Adafruit Feather® boards with the intent to later add a RFM69HCW® radio link so that the monitors could communicate with a base station. Four Prototype 2 units were built in 2017. The radio link functionality was implemented in Prototype 3 units for 2018, which were otherwise identical to Prototype 2 units. Twenty-five prototype 3 units were built (Fig. 2).

2.2. Assessment of the portable Doppler unit

Evaluating a beehive activity monitor based on the Doppler radar principle as a tool for assessing honey bee colony health first involved a preliminary assessment of the Doppler unit and then involved three experiments or phases. The first phase was a proof of concept that honey bee activity at the hive entrance was an indicator of hive population size and thus colony health. The second phase involved assessing if the Doppler beehive activity monitor measurements (RMS) correlated with visual counts of bee activity at the front of hives. The third, and final phase, involved using the Doppler beehive activity monitor measurements (RMS) to predict colony health.

2.2.1. Preliminary assessment

The Doppler recordings of honey bee activities were digitized as WAV files using Prototype 0, and compared to visual counts of bee forager flights leaving and coming back to a colony housed in a standard Langstroth hive (located in Orono, ME, USA). The visual counts of bee forager activity were recorded with a handheld clicker tool (LUPO® 4 Digit Hand-Held Digital Tally Counter 9999). We assessed the relationship between the RMS recordings from the beehive activity monitor and the honey bee foraging visual observations graphically. Furthermore, visual counts of foragers were compared to Doppler tracks obtained from recordings using the Prototype 0 unit. The audio frequency (20–500 Hz) output of Prototype 0 was digitized using a digital audio recorder, and saved as a WAV file. The data was processed using a MATLAB® script, and time–frequency-intensity plots were generated to show all individual forager bees flying at that time span (90 s of recording simultaneous to manual counts). These forager tracks were counted and averaged to correlate visual counts with radar results taken over the same time span.

2.2.2. Phase I – Honey bee activity at entrance to hive as a measure of colony health

Honey bee hives used in the Phase I study in 2017 were located in Orono, Maine, USA, at four apiaries. Eleven colonies (set up in Langstroth hives) of varying colony health were used (3 weak colonies possessing 1–3 frames of brood and workers, 4 moderate strength colonies possessing 3–8 frames of brood and workers, and 4 strong colonies possessing more than 8 frames of brood and workers). To determine if honey bee activity at the hive entrance correlated with colony health, a handheld clicker was used to record forager bee traffic at the front entrance of the hive and later compared to the colony's health after count measurements were taken for several days. Forager bee activity (Frazier et al., 2015) was chosen to be monitored over general colony activity (see above) because our experience suggested that it is more accurate for the observer to measure incoming and outgoing bees at high velocities than to count bees that exhibit general non-directional short distance walking and flight activity. This is because general activity (McElroy, 2017) such as orientation flight and guard bee behavior have rapid, non-linear, short distance walking and flight patterns that make it difficult for the human eye to count without redundancy and inaccuracy. The assumption we made was that counting only forager bees as a measure of colony health values should be highly correlated with a measure based upon counting both forager bees and general bee activity as a measure of colony health.

Visual counts of incoming and outgoing bees were conducted from 12 to 20 July 2017, between 13:00 and 14:30 hrs, the usual period of peak activity for forager bees (Voeller, 2017). Count duration lasted 90 s for each measurement, a single trial. There were six trials per hive each day (3 trials for outgoing bees and 3 for incoming bees). Total bee activity was the sum of incoming and of outgoing forager bees. Incoming bees were counted only if the bees fully entered the hive, as robbing bees from other hives are usually apprehended and prevented from entering the hive by guard bees, and orientation flight bees are not yet aiding in the productivity of the hive. Therefore, these bees were excluded from the count and only returning foragers were counted. Determining forager outgoing bees was distinguished by their behavior; which can be described as a rapid linear motion outward from the hive.

It is known that activity and productivity of colonies are disturbed for several days after a hive is opened (Butler and Free, 1952). To avoid this, colony health was evaluated after all activity measurements were taken over a time span of three days on moderately sunny days with an average daily temperature of 23 to 25 °C. We used colony population size (the summation of worker bee population and brood population) as an indicator of colony health (Ostrofsky, 2015; Miranda et al., 2016).

To measure population size, the number of capped or sealed brood[1] and workers per frame were estimated using a frame tool that was split into 2 quadrants, 8 sections, of 110 cm^2 per section. The proportion of coverage per frame was estimated as the number of sections covered by worker bees and repeated for capped brood for both front and back of each frame. Proportion of workers and brood per frame were determined using Eq. (2) show below:

$$\left[\frac{(Quadrants\ \ of\ \ frame\ \ filled)(surface\ \ area\ \ of\ \ one\ \ quadrant)}{(Total\ \ surface\ \ area\ \ of\ \ frame)}\right] * (Capacity\ \ of\ \ workers\ \ or\ \ brood) \quad (2)$$

Total number of workers and brood in the colony was determined by accounting for frame size, derived from Delaplane et al. (2013), and then applying Eq, (2). All equations were based upon North American frame types; Langstroth deep frame, medium frame, and shallow frame. The metrics Deleplane et al. (Delaplane et al., 2013) used for each of these frames are in Table 1 and assume worker brood cells occupy 3.9 cm^2.

2.2.3. Phase II – Visual honey bee activity compared with Doppler measure of bee activity at the hive entrance

Honey bee colonies were evaluated from 30 June to 5 July and again from 27 July to 1 August 2017. Visual counts of forager bee activity were recorded using a handheld counter as described in Phase I (Section 2.2.2, above). Six hives at the Grove Street Extension apiary (University of Maine, Orono, ME, USA) were observed in order to determine whether the Doppler RMS signal measured levels of honey bee activity that were specific to each colony. Six Doppler units (one per hive) were placed to collect RMS measurements of colony activity. Activity trials for these six hives were performed during set hours of the day, ranging from 8:00 to 11:30, 12:00 to 15:00, and 16:00 to 20:00 hrs.

Each trial was 90 s long and repeated (3 replicate measures for each colony). Measurements were taken on at least three separate days for each hive. Visual counts were time stamped and equivalent RMS measurements matched with the visually recorded count times were retrieved from the Doppler devices' memory cards and summarized using algorithms coded in the MATLAB programming language (MathWorks Inc., 1996). Counts and RMS values were averaged per day.

A second set of trials were performed from June 2018 through September 2018 between 10:30 and 14:00 PM on fourteen Langstroth hives of varying strength. Three of the hives were located on the University of Maine campus (Orono, ME), three on Rogers Farm Forage and Crop Research Facility (Stillwater, ME), five at a private residence in Hampden, ME and three at a private residence in Jonesboro, ME.

In the second trial, third generation prototype Doppler hive monitoring units were installed directly to each hive's bottom deep box roughly five centimeters above the hive entrance with the radar sensor located at the center. Every unit had an accompanying solar panel that was secured facing south to the hives telescoping outer cover. After fifteen seconds of a unit being powered on, the RMS of the return signal due to bee activity collected for thirty seconds was calculated, and saved to a micro-SD memory card inside the unit for storage. This process was repeated every five minutes throughout the monitoring period.

Visual counts during the second trial were conducted between 10:30 AM and 2:00 PM using a tally counter. A trial was comprised of 90 s counting forager egress, followed by 90 s of counting forager ingress. Two trials were conducted during the field season for each hive monitored prior to colony population assessments. Visits to hives were also conducted biweekly to download stored RMS data from the monitor's memory card. The data was then taken back to the laboratory and summarized as described previously.

2.2.4. Phase II – Beescan™ honey bee count activity correlation with Doppler radar measurements of honey bee activity at the hive entrance

In order to better assess both the general and forager activity at the front of the hive compared to the Doppler measurements, an experiment was conducted from 27 July to 2 August 2017 utilizing an optical bee counting device, Beescan™ (Lowland Electronics, Belgium). Beescan is comprised of 32 bi-directional tunnels that sit in front of the hive entrance and force the bees to access the hive only through the tunnels. Each tunnel houses two parallel beams of red light so that a bee's flight of orientation (in or out) can be determined by which beam is broken first by the bee's body. The Doppler beehive monitoring unit and Beescan sensors measured activity with differing time frame lengths. The Beescan measured data continuously and saved the results in ten-minute intervals. The Doppler beehive monitoring unit executed activity measurements every 5 min for 30 s periods. Therefore, in order to achieve an RMS value matched to every Beescan activity point, all time stamped RMS values within the ten-minute span were averaged and

[1] Capped brood were counted and not uncapped brood as capped brood indicated current progression into adulthood, and thus a stronger likelihood of survival for the individual bee.

Table 1
Metrics used for equations to assess colony population size. All frames are North American dimensions.

Frame type	Surface area (cm^2)*	Maximum number of workers*	Maximum number of sealed brood*
Deep hive body	1760	2430	7040
Medium hive body	1310	1820	5240
Shallow hive body	922	1280	3688

* Both sides of frame.

compared to the time stamped Beescan count data. In addition, an onsite weather station recorded air temperature and solar radiation. This experiment was repeated with one hive at the University of Maine campus in Orono, ME from July 2018.

2.2.5. Phase III – Colony health predicted by Doppler beehive monitoring unit measurements of honey bee activity at the hive entrance

Four hives from the Grove Extension Apiary between 13 and 27 September 2017, were evaluated between 13:00–14:00 hrs. The Doppler measurement consisted of three consecutive 90-second intervals per hive where RMS was recorded and then averaged for the entire measurement time period. Recordings were taken for 5–6 days within a one-week span before health of hives were assessed the following week. Colony health was assessed in the same manner as described in Phase I (Section 2.2.2, see Table 1). In 2018, colony health was assessed the same way as the prior season (2017), but with the fourteen hives described in Section 2.2.3.

2.2.6. Graphical and statistical analysis

Visual inspections of graphs representing Doppler beehive monitoring data collected in the preliminary study (Section 2.2.1) and the Beescan unit measures vs. Doppler beehive monitoring unit measures in the study relating bee activity to RMS (Section 2.2.4) were conducted. Graphs were constructed in Excel™ and visual comparisons were made between the Doppler output in WAV or RMS units and bee activity. More rigorous statistical models were then used to test our hypotheses in Phases I - III.

General linear models were used to test the hypothesis that: a) visually measured honey bee forager activity predicts colony health as measured by total larval and adult honey bee colony size (Phase I, Section 2.2.2) b) visually measured honey bee forager activity predicts the RMS signal from the Doppler beehive monitoring unit (Phase II, Section 2.2.3), and c) the Doppler beehive monitoring unit RMS signal predicts colony health (Phase III, Section 2.2.5).

All modeling was performed using the JMP statistical software platform (SAS Institute, 2017). Models were fixed effects models. Independent variables were: 1) the categorical variable, study representing the two studies (mid-summer and early fall) in 2017 and the one study in 2018; and 2) the continuous variables: visually measured honey bee forager activity, RMS magnitude of the measured Doppler signal, and colony health (based upon colony population size). A measure of colony health that we first evaluated was the sum of honey bee workers and sealed brood. We also evaluated, as measures of colony health, the sealed brood to honey bee worker ratio and the product of: 1) the sum of honey bee worker and sealed brood, and 2) the sealed brood to honey bee worker ratio. All measures used as dependent variables in the three statistical models were initially tested for normality based upon the Shapiro-Wilk W test (Shapiro and Wilk, 1965). Without transformation, the RMS signal was found to be a Gaussian distribution. Bee activity was square root transformed and colony health was logarithm (base 10) transformed to provide variates with no significant departure from the Gaussian or Normal distribution.

All models included the effect of study (2017 and 2018) and its interaction with the independent predictor variable. We first ran saturated models with the study-interaction term. If the interaction was not significant ($P > 0.05$), we removed the interaction (pooled the degrees of freedom into the error term) and reran the model (Hines, 1996). Once final models were derived, we inspected plots of studentized residuals to assess homogeneity of variance and tested the model residuals Normality using the Shapiro-Wilk W test.

A fourth general linear model was used to determine if the weather conditions of air temperature, relative humidity, and solar radiation significantly accounted for the unexplained variation observed in the Phase I model (hypotheses: visually measured honey bee forager activity predicts colony health as measured by total larval and adult honey bee colony size). In this model colony health was the dependent variable and the independent variables were: study, honey bee activity, air temperature, relative humidity, and solar radiation during the time period in which the bee activity was measured. The weather measurements were obtained from a weather station setup and maintained in the apiary where the hives were located in 2017; and by the nearest NOAA weather station in 2018 (National Climatic Data Center, 2018).

3. Results

3.1. Preliminary assessment

Preliminary 90 s WAV file digitized output of forager activity measured by Prototype 0 were counted and compared to visual honeybee counts. Measured visual honey bee forager counts explained 55% ($r^2 = 0.550$, $P < 0.0001$) of the variance in Doppler signal strength recorded from the 10.5 GHz radar. In addition, individual bee foragers leaving from the hive and returning to the hive can be tracked by the Doppler unit (Fig. 3 represents a 12 sec. sample). The departing forager

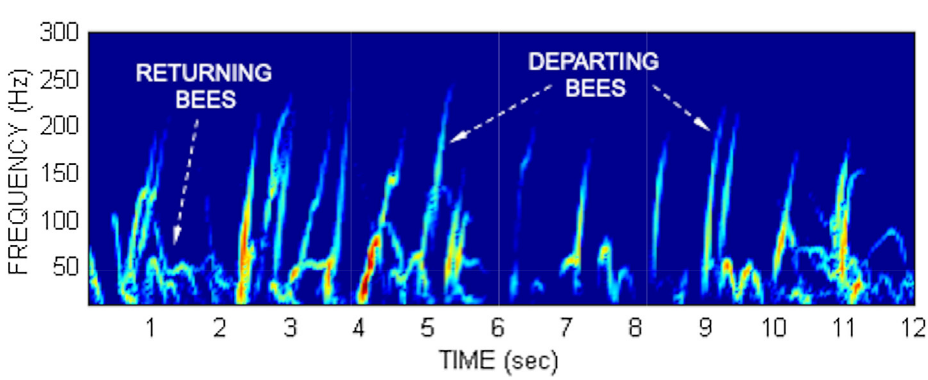

Fig. 3. Time-frequency-intensity heat map plot from the Prototype 0 beehive activity monitor (10.5 GHz radar). The frequencies of forager bees are the vertical tracks approaching 90–150 Hz with yellow and red banding. Tracks can be seen extending throughout the 12 s timeframe of the recording from left to right. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

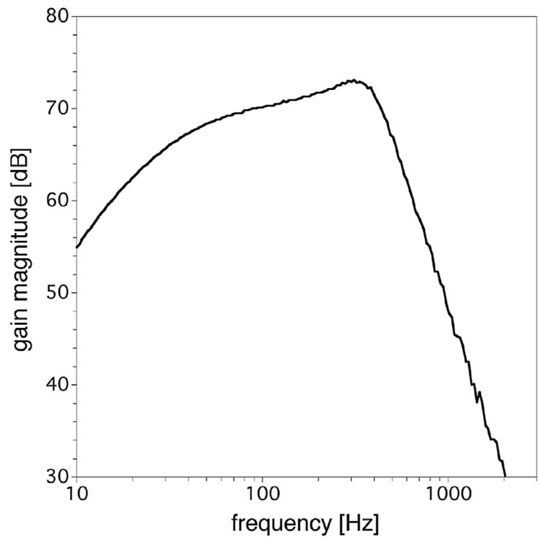

Fig. 4. Magnitude response of the active bandpass filter on Prototype 3–03, from 10 Hz to 2 kHz.

bees have a constant acceleration between 5 m/s^2 and 7 m/s^2, and the highest measured frequency was 250 Hz, limited by the gain of the amplifier.

The active bandpass filter magnitude response, measured using a Digilent Analog Discovery 2® instrument is shown in Fig. 4. The measured peak gain was 73 dB at 333 Hz. The gain at 50 Hz is 68.5 dB and drops to 55 dB at 10 Hz. A week's worth of RMS data collected using the same unit is shown in Fig. 5. The noise floor was 50 mV, due to the noise on the 1.65 V reference voltage for the amplifier, which is powered by a 3.3 V single-ended supply. For a pure sinusoidal input with 1.65 V peak, the RMS voltage would be 1.167 V. The maximum recorded RMS voltage was 1.41 V, indicating that the amplifier output was saturating due to a large number of bees flying in and out of the hive at that time.

3.2. Phase I – Honey bee activity at entrance to hive as a measure of colony health

The results for Phase I of our study provided evidence that visually assessed honey bee forager activity (square root transformed) explained

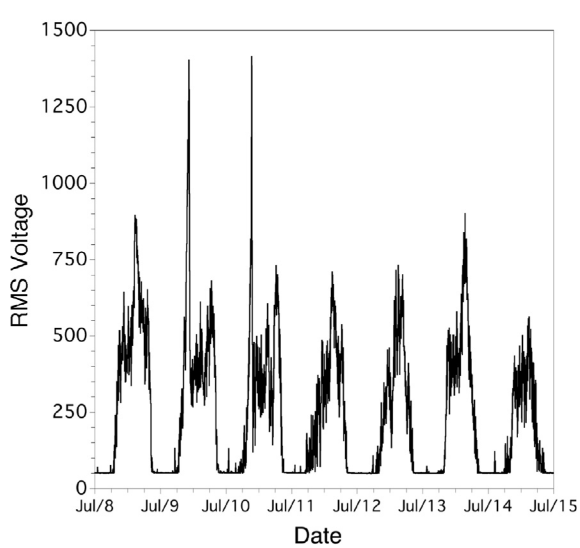

Fig. 5. RMS voltage data collected over one week (8 July − 14 July 2017) using P303.

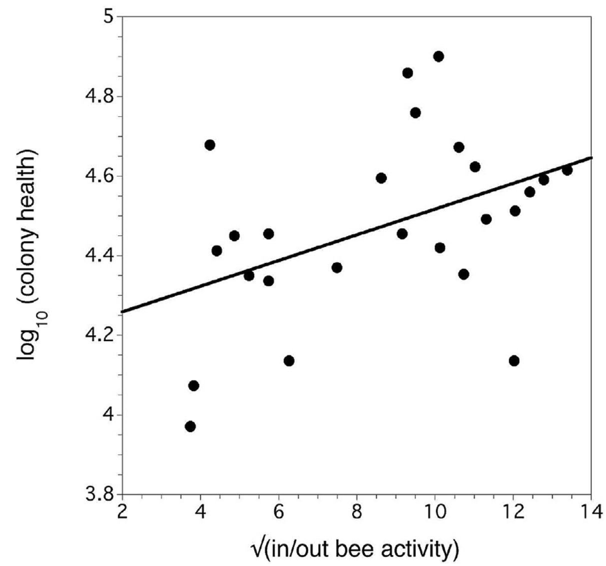

Fig. 6. The relationship between honey bee forager activity at the hive entrance (square root transformed) and colony health (logarithm transformed colony population abundance). Data was from 25 hives measured in three studies over two years (2017 and 2018).

a significant level of variation in honey bee colony health (logarithm transformed) ($F_{(1,21)} = 9.422$, $P = 0.006$, $r^2 = 0.433$, Shapiro Wilk W: $P = 0.709$). A multiple regression model demonstrated that inclusion of weather measures (air temperature, relative humidity, and solar radiation) in addition to measured bee activity did not improve prediction of colony health. Fig. 6 shows the relationship between honey bee activity at the hive entrance and colony health.

3.3. Phase II - Doppler measures of bee activity

3.3.1. Phase II – Visual honey bee activity correlation with Doppler measure of bee activity at hive entrance

Results for Phase II suggested that visual counts of honey bee activity is strongly predictive of the RMS Doppler bee hive monitor signal ($F_{(1,6)} = 11.949$, $P = 0.013$, $r^2 = 0.766$, Shapiro Wilk W: $P = 0.203$). Fig. 7 depicts this relationship.

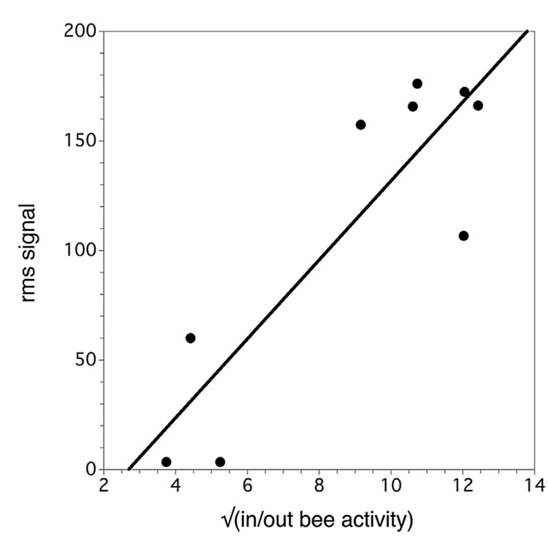

Fig. 7. Relationship between honey bee forager activity at the hive entrance (square root transformed) and Doppler unit RMS signal at the hive entrance (n = 9 hives, 2017–2018).

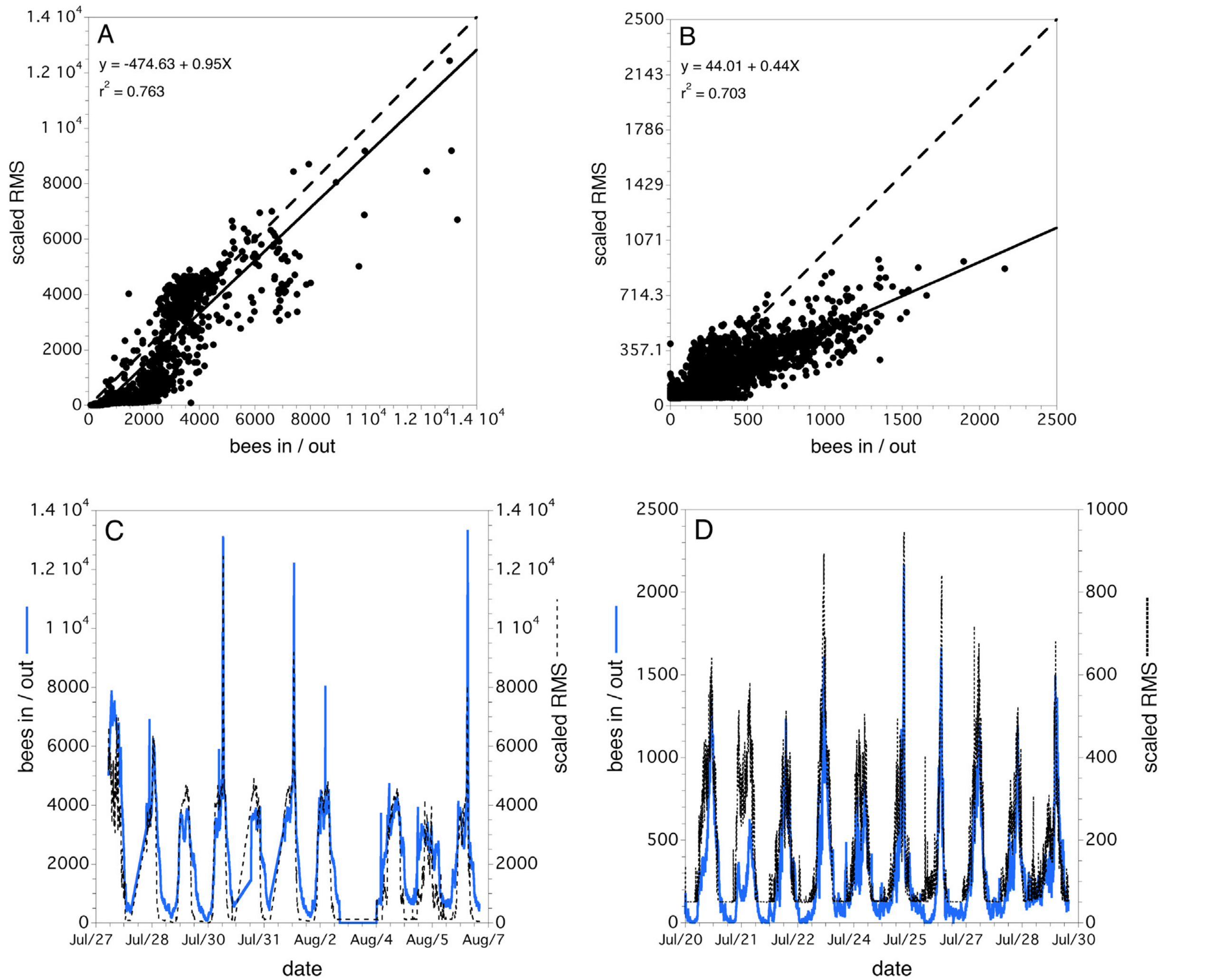

Fig. 8. Relationship between in/out honey bee activity measured by the optical Beescan™ device vs RMS in 2017 (A), 2018 (B), and over time, 2017 (C), and 2018 (D). Solid line in figures A and B is the least squares regression line and the dashed line is the 1:1 slope.

3.3.2. Phase II – Beescan™ honey bee count activity correlation with Doppler radar measurements of honey bee activity at the hive entrance

Data collected from the Beescan unit was utilized as an additional measure of honey bee activity and furthered our efforts to validate the relationship between honey bee in + out activity and the Doppler unit RMS signal. Both in 2017 and 2018 (Fig. 8A and B) honey bee activity at the hive entrance, measured by the Beescan unit, explained a high percent of the variation in the Doppler RMS signal. This indicates that the RMS signal reflects honey bee in/out activity and is a very good proxy for colony activity. Fig. 8C and D show that the rhythmic diurnal activity and peak honey bee foraging is measured almost identically with the optical Beescan unit and the Doppler radar.

3.4. Phase III – Colony health predicted by Doppler radar measurements of honey bee activity at the hive entrance

The Phase III study demonstrated that our portable Doppler beehive monitor unit deployed at the hive entrance explains a high degree of the variation in colony health (log transformed total colony brood (larval) and adult densities) ($F_{(1,6)}$ = 9.989, P = 0.026, r^2 = 0.731, Shapiro Wilk W: P = 0.637). Fig. 9 depicts this predictive relationship.

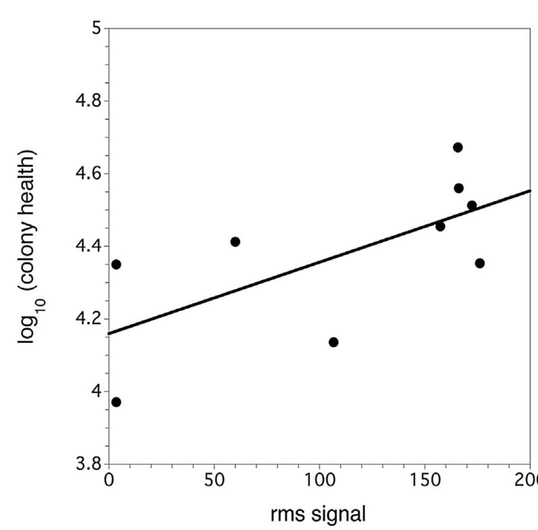

Fig. 9. The predictive relationship between RMS Doppler signal and colony health as measured by colony honey bee population size, logarithm transformed (n = 9 hives, 2017, 2018).

4. Discussion

This study investigated a novel method of assessing honey bee colony health with a Doppler beehive monitoring unit. We assessed three phases studying the relationship between: Phase I) determine if a relationship existed between forager activity and colony health; Phase II) determine if Doppler bee hive monitoring unit RMS was correlated with forager activity; and Phase III) determine if Doppler bee hive monitoring unit RMS was predictive of colony health measured as the total sum of brood and worker population in a colony. The results of our study showed that a portable Doppler unit is an excellent tool for monitoring honey bee colony health.

4.1. Instrument characteristics

The bee hive monitors were tested in the laboratory and in the field, and performed their functions as designed. Three of the 2018 units were operational from early June to late October. The 2000 mAh battery and 1 W solar panel were sufficient for continuous operation of these units. No power outages were recorded.

The amplifier design was standardized for the Prototype 2 and Prototype 3 designs. The voltage gain at 100 Hz ($v_{bee} = 1.4$ m/s) is 70 dB, while the gain at 200 Hz ($v_{bee} = 2.8$ m/s) is 71.7 dB. These faster moving bees would be twice as far away from the bee hive monitor, resulting in the return signal being 24 dB below the slower moving bee. Thus, the present amplifier design allows the measurement of the general activity levels, but cannot determine the forager bee activity levels. A narrower bandwidth amplifier with a sharper cut-off would be needed to measure the forager bee activity independently from the general activity. Measuring forager activity vs. general activity may provide another indicator for hive health and growth.

The input signal can have an 80 dB range, as bees fly from the hive entrance to a distance of 1 m, the detection range for the current system. A logarithmic gain amplifier could have been used to compensate for the smaller signals. However, the results indicate that a linear amplifier is sufficient. As Fig. 5 indicates, the root-mean-square of the AC signal can be used even when the amplifier output might be saturated at a given instant. For a pure sinusoidal input with 1.65 V peak, the RMS voltage would be 1.167 V. The maximum recorded RMS voltage was 1.41 V, indicating that the amplifier output was saturating due to a large number of bees flying in and out of the hive at that time.

The noise floor of the instrument ranged from 30 mV to 50 mV RMS. This noise is dominated by the noise on the 1.65 V voltage reference line. Any noise on this line is also amplifier by the gain of the amplifier. The noise performance can be improved by switching to a printed circuit board design, and separating the analog and digital supply voltage planes.

4.2. Bee hive monitor performance and validation

The results from *Phase I* show that foraging activity explained a significant amount of the variation in the hive population of brood and workers ($r^2 = 0.433$). The relationship observed is similar to previous work that showed a relationship between brood, colony population and foraging behavior where larger numbers of brood increased with foraging activity (Eckert et al., 1994). As pollen is the only natural source of protein for brood and workers (Brodschneider and Crailsheim, 2010), it stands to reason that a colony with higher brood population requires larger amounts of pollen, thus increasing foraging; barring phenological factors (i.e. lack of pollen plants in bloom). Pollen foraging measured in the field has been shown to have a direct impact on overall colony health (Smart et al., 2016). Our results corroborate this by showing that foraging activity explains significant variation in colony population abundance, a proxy for colony health. In addition, worker populations are highly associated with brood populations (Storch, 1985; Khoury et al., 2011). In our study this was also the case ($F_{(1,23)} = 6.554$, $P = 0.018, \beta = 0.456 \pm 0.178$). Our data also showed that brood was a consistent ratio of the worker population (ratio of brood to worker = 0.88 ± 0.09 (s.e.)). Therefore, we conclude that as brood population increases, worker population increases and the more likely it is that high forager activity at the hive entrance will result.

In Phase II of this study, we demonstrated that the Doppler beehive monitor unit RMS measurements predicted visual assessment of foraging activity rates, suggesting that RMS is a good proxy for actual honey bee foraging activity. These results are based upon hives of differing population sizes with various intensities of activity throughout the day. This also indicates that this is a robust relationship despite variation in the quantity of honey bees at the entrance due to a mixture of foraging and general activities such as ventilation, guarding the entrance, and orientation flights. It is not obvious that this relationship would be robust because the hive entrance is characterized by complex behavioral activity (Storch, 1985) unique to bees that forage under changing weather conditions. Weather can have a substantial impact on hive activity at the entrance that increases as colony size increases (Danka and Beaman, 2007; Frazier et al, 2015). Under high ambient temperatures, honey bees may exhibit several behaviors. They may aggregate at the front of the hive and beat their wings quickly, in order to recirculate air– a behavior known as *fanning* (Seeley, 1995). They may also demonstrate *bearding*, a phenomenon where a large quantity of bees will collect around the hive entrance during periods of intense heat to reduce metabolic heat in the hive. This group behavior maintains internal hive temperatures leading to colony homeostasis (Ostwald et al., 2016). All of the bee activities at the hive entrance are important in holistically assessing the vitality of the hive (Seeley, 1995). In Fig. 7 it was demonstrated that the optical device, Beescan, was useful in validating the Doppler radar's capability to measure bee activity ($r^2 = 0.703$ (2017) and $r^2 = 0.763$ (2018), $P < 0.010$ and $P < 0.001$; respectively). However, devices such as Beescan are able to detect honey bee entrance and exit from the hive, but not able to assess whether those bees are still at the entrance or in flight (Struye, 2001). The Doppler radar's RMS predicted bee activity that is above the levels of bee activity measured by the Beescan unit. This demonstrates that the Doppler unit is able to measure honey bee behavior at the front of the hive (guarding, fanning or bearding) *in addition to* forager activity, thus giving a more complete assessment of a colony's overall bee activity levels.

The results from Phase III represent operation of our Doppler units when they were deployed on different colonies in two different years under different weather conditions. Despite this, the Doppler units were able to reliably explain a high degree of variance in colony health measured by brood and adult population density within hives ($r^2 = 0.731$, $P = 0.026$). While weather can have a significant influence on honey bee activity at the front of the hive (Danka and Beaman, 2007) and on foraging in the field (Drummond, 2016) and the Doppler unit is capable of detecting changes at the front of the hive entrance due to fluctuating temperatures (Souza Cunha, 2019), our results showed temperature, relative humidity, and solar radiation had no measurable effect on increasing the predictive capability of RMS for colony health across both studies. This is most likely due to the standardized conditions (warm and sunny) in which we measured both bee activity and colony health assessments.

Other portable colony assessment devices that are commercially available to beekeepers commonly measure one or several of the following factors as continuous variables: hive internal temperature, internal relative humidity, hive weight, and/or forager activity. Utilization of in-hive temperature (thermocouples) and moisture and gas sensors (relative humidity, O_2 and CO_2) have also been used as measures of colony health via population-level metabolic rates (Kronenberg and Heller, 1982). The uses of these devices have aided in quantifying colony health during winter seasons when honey bees are not active at the hive entrance (Milner and Demuth, 1921). However, acquisition of hive temperature and gas concentrations are most likely not uniform throughout the hive and therefore the accuracy of the measured gas and temperature readings may be dependent upon the location of the sensors within the hive and hive dimensions and construction materials, although see Kridi et al. (2016). In addition, genetic diversity of workers in the colony may affect these measures (Jones et al., 2004).

The weight of a hive has commonly been used as measure of colony population size, nectar flow, food reserves, and colony survival (McLellan, 1978; Harbo, 1993; McGrady et al., 2018) As a measurement, weight as a singular point at a given time is not always easy to interpret and analyze because hive weight integrates colony population size, but also pollen and honey stores (Buchmann and Thoenes, 1990). When utilized for continuous and automatic surveillance, weight can assess general hive population fluctuations due to colony respiration and nectar flux (Hambleton, 1925), but more serious deviations from population baselines due to mite infestation (Guzmán-Novoa et al., 2010; Le Conte et al., 2010) that would lead to rapid decline in foraging activity would be more difficult to detect because hive weight is mostly nectar and honey in established colonies, but mostly bees in newly introduced colonies (Hambleton, 1925). Notwithstanding the benefits of weight as a tool to measure colony health, weather factors such as temperature, precipitation and wind can affect colony weight and can confound the derived forager activity as measured by colony weight. Therefore, other monitors or load-controlled sensors are most likely required for hive weight and colony health correlations to maintain accuracy.

The use of most colony monitoring devices require either extensive cost, maintenance, or initial loss in bee productivity due to their general invasiveness within the hive. Therefore, the importance of external devices vs. internal devices is multi-faceted. The impact of having to install an internal device can cause an observer effect that influences data acquired (Rittschof and Robinson, 2013). Radio-frequency identification (RFID) tags introduced by Streit et al. (2003) have been an important tool for studying honey bee behavior. As with any device attached to an insect, there is the potential for variation in behavior due to presence of the device itself. For studies that investigate collective foraging behavior over individual behavior, Doppler radar would eliminate that variation, but also has the advantage of tracking individual bees depending upon the design and frequency of the Doppler unit (Aumann and Emanetoglu, 2016a; 2016b; Aumann et al., 2017). This aspect of interference or "observer effect" can also be seen in devices that "gate" the entrance by reducing it to several small entrance tunnels for single bees to enter and exit. These devices replace the hive bottom board and accurately detects bee movement, but may also provide variability in bee behavior through congestion if not enough entrance holes are present (Bromenshenk et al., 2015). Regular maintenance is required to prevent tunnels from becoming lined or blocked by pollen, resins, cuticular waxes and oils, and propolis (Tulloch, 1970; Simone et al., 2009), leading to unreliable data acquisition and arduous labor. Video based tracking devices provide data on incoming/outgoing bees as well as flight direction. They cause little to no interference with bee activity, but require high light conditions to accurately track honey bees. Color variance between the bees and background cause contrast issues where individuals might be indistinguishable from the background and therefore these devices might lack the sophistication to accurately measure bee activity of the entire foraging force (Babic et al., 2016).

5. Conclusion

While several honey bee colony monitoring devices are commercially available and can measure variables that reflect bee behavior, we suggest that there are few that directly do so in a way that consistently quantifies colony health. Our results indicate that use of Doppler radar in a bee hive monitoring unit is able to accurately measure colony foraging and that this activity dynamic is a good measure of colony population size which in turn is a good proxy for honey bee colony health. The monitoring device that we designed is a cost-effective tool for beekeepers to monitor their colonies, whether they have only one or several thousand colonies. This device may also provide valuable bee activity data in research studies that investigate pathogen dynamics or pesticide exposure. To improve upon the unit in following seasons we will be upgrading the quality of manufactured components, include an external thermometer, and account for *Varroa destructor* mite levels of tested colonies. The bee hive monitor will be migrated to a printed circuit board which will miniaturize the design and reduce the noise floor. The radio link will be enabled allowing for remote access to the data. Finally, a version of the monitor which will measure foraging activity and compare it with general activity is currently being designed.

CRediT authorship contribution statement

A.E. Souza Cunha: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing - original draft. **J. Rose:** Data curation, Formal analysis, Investigation, Validation, Writing - original draft. **J. Prior:** Investigation, Software. **H.M. Aumann:** Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing - original draft, Writing - review & editing. **N.W. Emanetoglu:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **F.A. Drummond:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compag.2020.105241.

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