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Evaluating a Doppler Radar Monitor for Assessing Honey Bee Colony Health

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EVALUATING A DOPPLER RADAR MONITOR FOR ASSESSING HONEY BEE COLONY HEALTH

AN HONORS THESIS

by

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ABSTRACT

Honey bees pollinate an estimated $15 billion worth of crops each year. It is therefore vital that beekeepers assess the productivity and health of colonies in order to reassure the reproductive future of this species. Modern techniques in which beekeepers can assess honey bee colony health are labor intensive, costly, and invasive to the bees as they must open and rearrange the hive to assess colony health. A radar-based sensor, placed outside of the hive, can be used to assess colony activity and health in a non-invasive manner. In order to validate the function of this hive monitor and quantify colony health several colonies were studied with three objectives: (i) Objective I looked to affirm that bee activity was a good predictor of colony health. The relationship between honey bee colony health and hive activity of eleven hives were observed over the course of a week and then assessed for health status by estimating brood (immatures) and adult population size (total frame area occupied per colony) (ii); Objective II looked at the activity indices derived from the radar output were correlated with counts of foraging bees determined through the use of a manual counter (bees/second), an optical sensor, counting the Doppler signature tracks in recorded radar data and weather conditions; and (iii) the activity indices (RMS) vs colony health were observed for five hives over the course of two weeks. Results were characterized by statistically significant correlations in all objectives. A model was constructed in Objective I that resulted in an r^2 of 0.84. This model confirmed that the radar-derived activity index was a good measure of bee activity. It also showed that solar radiation was the best weather factor predicting bee activity. Objective II affirmed that bee activity was a good predictor of colony health with an r^2 of 0.53. Objective III affirmed that radar-derived activity was a good predictor of colony health with an r^2 of 0.56**.** This

data provides evidence that the radar-based hive activity monitor is a viable tool for monitoring honey bee colony health.

ACKNOWLEDGMENTS

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s = distance traveled by the wave
t = time

$$T = (1)/f$$ .... (1.2)

$$c = \lambda f \rightarrow f = \frac{c}{\lambda}$$ .... (1.3)

$$f_D = \frac{2v_o}{\lambda}$$ .... (1.4)

$$f_D = \frac{2v}{\lambda} cos\alpha$$ .... (1.5)

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$$\left(\frac{(\text{Quadrants filled side 1 of frame})(110) + (\text{Quadrants filled on side 2 of frame})(110)}{\text{Area of oneside of the frame} * 1759\text{cm}^2}\right) * 200 = \%\left(\frac{\text{workers}}{\text{frame}}\right)$$ .... (2.1)

$$y = 0 + 12.15x$$ .... (2.2)

$$y = 0 + 9.1x$$ .... (2.3)

LIST OF ABREVIATIONS/TERMINOLOGY

Apiary – colonies, hives, and other equipment assembled in one location for beekeeping operations; also known as a bee yard.

Brood – young honey bees. Immature bees that have not yet emerged from their cells as adults. Brood can be in the form of eggs, larvae, or pupae of different ages.

Capped brood - during the entirety of their non-feeding pupal stage pupae whose cells have been sealed with a porous cover by mature bees to isolate them during the entirety of their non-feeding pupal stage; also called sealed brood.

CCD – Colony Collapse Disorder. The slow dwindling disappearance of the majority of worker bees in a colony, resulting in only brood and a queen and the subsequent death of the colony. The causes of the phenomenon are unclear, though many possible causes or contributory factors have been proposed, such as parasitic mites, diseases, pathogens, pesticides, and changes in habitat.

Forager bees – older worker bees searching for a new source of pollen, nectar, propolis, water, or a new home for a swarm of bees.

Frame – a moveable portion of the Langstroth beehive; a beehive being a box with several movable frames makes up the space in which honey bees will produce wax, honey and care for brood.

Nectar - a sweet and often fragrant liquid secreted by the nectaries of flowers for attracting animal pollinators. Nectar is the raw product of honey.

Robbing - stealing of nectar, or honey, by bees from other colonies which happens more often during a nectar dearth.

RMS – Root Mean Square. The square root of the arithmetic means of the squares of a set of values, used as a measure of the typical magnitude of a set of numbers, regardless of their sign.

Supercedure – the natural replacement of an established queen with a new queen raised by the workers in the hive.

Swarm - a large number of worker bees, drones, and usually the old queen that leaves the parent colony to establish a new colony by the mechanism of fission.

Swarming - the natural process of propagating a colony of honey bees through the process of swarming.

Worker bee - a female bee whose reproductive organs are undeveloped. They are the daughters of the queen in the colony. The majority of the honey bees are worker bees and they do all the work in the colony except for laying fertilized eggs.

CHAPTER ONE

INTRODUCTION

1.1 Background on Sensor Needs

It is estimated that 90 percent of all wild flowering plants depend on animal pollination (FAO, 2016). In addition, over the past 50 years, the utilization of animal pollinators has increased agricultural yield by 300% (FAO, 2016). Of those pollinators, honey bees are one of the major insect pollinators. In the United States, honey bees contribute to the pollination of 15 billion dollars' worth of crops a year. In more relatable terms, this means that 1 one in 3 bites a citizen of the U.S takes of their food is either directly or indirectly pollinated by a honey bee (Sass, 2011). Bees not only contribute to a large quantity of harvest but also a vast variety. Apples, berries, cantaloupes, cucumbers, alfalfa, and almonds are all very dependent on the pollination that honey bees provide (Sass, 2011).

Honey bees do not only affect us on global and national levels but also have a strong presence locally, here, in the state of Maine. The Maine wild blueberry industry is over 150 years old and contributes to a large part of the state's economy. For Maine wild blueberry farmers, the struggles have mainly been facing challenges from global oversupply of cultivated berries and steeply declining prices; yet recently, the issue that faces most farmers is crop production. It was stated that Maine's wild blueberry crop has decreased nearly 50% this past year (from 2017 to 2018) and experts suggest that it is due to the lack of pollination from the declining number of pollinators, such as honey bees. Usually, 80,000 hives of bees are imported to the state ever year but this past year just under 28,000 hives were transported due to the increase in the price of hive rentals, which indirectly is due to the declining number of pollinators (Yarborough et al. 2017). Therefore, Colony Collapse Disorder (CCD) is a very prominent issue to the future of the industry of food pollination and honey production in Maine's highly agricultural economy.

The decline in imported bees is due to the unfortunate fact that the bee population has been decreasing steadily for the past few decades[1] (VanEngelsdorp, 2008). This loss in honey bee population has been due to Colony Collapse Disorder (CCD). The cause for CCD has been officially defined by environmental and biological scientists as not one specific problem but the accumulation of one or two various factors that affect colony health such as: climate change, pesticide usage, loss of natural habitat, viruses and parasites such as Varroa mites (Bessin, 2016).

Since the day that apiarists first noticed honey bee population decline, researchers and apiarists alike have been working hard to decrease the effects of CCD on honey production. This thesis acknowledges recent research from the USDA that has shown that CCD has decreased by 27% across the United States, and in the state of Maine CCD dropped from 60.5% to 23.3% (Steinhauer et al., 2015, 2017). Some recent progress in decreasing the rate CCD have come from bans on certain pesticides which were found to have adverse effects on colony growth; however, the majority of overall decrease has less to do with honey bee population comeback and more on the improved tactics with which beekeepers use to counteract colony losses. As Harvard University beekeeper and the vice-president of the American Beekeeping Federation based in Atlanta said,

> "You create new hives by breaking up your stronger hives, which just makes them weaker…We check for mites, we keep our bees well-fed, we communicate with farmers, so they don't spray pesticides when our hives are vulnerable. I don't know what else we can do." (Bjerga, 2017).

This information suggests that the decrease in CCD is driven by improvement in areas of parasitic mite and pesticide research and inflated by the ability of beekeepers to find quick solutions: shuttling honey bees from one apiary to another and breaking up stronger colonies into weaker ones. These temporary solutions have attributed to stabilizing CCD numbers but by no means have increased the health of the overall honey bee population. Thus, the mass loss of honey bees per year due to colony collapse disorder continues to plague the food industry as it has become very costly for farmers to ship more bees from other states in order to sustain their farms.

It is therefore vital that beekeepers be able to monitor the health of their colony. The most common methodology used by beekeepers to examine colony health is to internally examine the hives. This is done by manually opening the hives and examining the hive habitat for signs of health, such as population size, queen supercedure cells, the queen herself, disease, parasite symptoms and honey production. The issue with this is that in order to have a comprehensive idea of how healthy a colony is the entire hive must be examined; meaning, that beekeepers will have to laboriously go through each and every frame within each hive. Not only is this time consuming, but it is also an invasive procedure in which many bees are crushed during the movement of frames and boxes thereby furthering the issues of colony health and population decline. Other internal methods of hive observation include sensors on the market, such as *Arnia*® and *Bee Smart Technologies*®. These devices include technology that measures various factors within the hive such as: temperature, humidity, acoustics and weight change (possible honey production). The idea is that through monitoring various factors a beekeeper can be more informed about the state of their colonies. Nevertheless, these sensors involve opening up and even deconstructing hives for installation/continuous maintenance as bees will seal the invasive sensors over with resins called propolis. Both sensors are invasive, require labor and are expensive, especially for large honey bee farms that can be comprised of several thousand hives.

It is evident then that there is a need for research into simpler, less invasive, methods to assess colony health, such as honey bee worker activity that is observable at the hive entrance. There is evidence that activity of bees coming and going from the colony are a sign of colony health (Storch, 1985). The "front of a hive," also known as the entrance, is a place where complex interactions between honey bees occur. For the most part, 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 bees orienting themselves with their environment at 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 (Storch, 1985). The decrease in this general activity is known to be a sign of a weakening or a distressed colony (Storch, 1985) 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 honey bees. 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 hive. Often, honey (a substantial portion of weight of the hive) is used to determine the productivity and therefore health of the colony, however, by simply monitoring the activity of the bees responsible for that productivity a good estimate for the health of the hive can be achieved (Frazier et al., 2015).

There have been attempts to measure hive entrance activity through the use of optical sensors such as *BeeScan*® (Appendix Fig.A.1) and through image recognition. The problems arising with this type of sensor is that optic sensors require: a) deconstructing the hive for initial installation and b) cleaning daily as pollen residue carried by bees become distributed on the sensor causing a decline in the sensor's efficiency. Cleaning 40 to 50 entrance tunnels per hive daily becomes a laborious task on a honey bee farm with hundreds of hives. Therefore, the optic sensor is not an ideal device for commercial use. The problems arising with the latter device, image recognition, is that the technology is complex and expensive to build and therefore the cost per unit is cost-intensive for beekeepers to invest in.

The question then becomes, "How can we produce a sensor which measures bee activity at the hive entrance that is non-invasive and allows quantification of honey bee colony health?" The solution is technology that is in use; everyday: a Doppler radar.

Doppler radar technology is used to measure the speed of a moving objects, such as a car traveling down a road. It is based on the Doppler effect, which is defined as a change in frequency or wavelength of a wave reflected from a moving target and measured by a stationary observer, wave source or radar (Giordano, 2009). This principle applied to the current project allows the determination of the bees' velocity relative to the electromagnetic wave emitter or radar.

The Doppler radar uses radio waves, which are electromagnetic waves ranging from 3kHz to 300 GHz. The wave is emitted from the device and reflected by the moving bee(s). The reflected wave that is received from the moving bee can tell us about the direction and velocity of said bee. In short, the compression or expansion of the wave is a function of direction of the bee's flight direction, and the amount of change from the received signal's frequency (from the emitted signal) is a function of velocity. An in-depth explanation of the mathematics that describe the Doppler radar is described in the next section.

1.2 Derivation of the Doppler Shift Equation

In Doppler radar, a radio frequency (RF) electromagnetic wave of known frequency (f) and velocity (v) is emitted, and travels over a certain distance (s) until it reflects off of a moving object moving either away or toward the hive (positive or negative $s + \Delta s$). As the object moves further away from the radar, the distance between each wave peak increases (Δs), which is graphically represented as an increase in period (an increase in wavelength). Therefore, a returning signal that is represented as a compressed wave will represent an object that is moving towards the radar and a stretched wave tells us that the bee is flying away from the radar. This is mathematically shown by the equation 1.1 and visually by the image below:

$$c = \frac{2s + 2\Delta s}{2t + 2\Delta t} = \frac{s + \Delta s}{t + \Delta t} \propto \lambda \qquad (1.1)$$

s = distance traveled by the wave
t = time

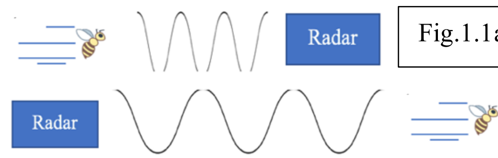

Fig.1.1a

The change in modulation of the signal, or in simpler terms, the change in frequency of the observed signal is explained by equation 1.2 where if the observed wave length (**λ**) has an inverse relationship with frequency. Therefore, an increase in wavelength is a decrease in frequency. Thus, stating that the value of the change in frequency of the sent/received signal is the indirect consequence of a change in RF wavelengths over time,

$$T = (1)/f \qquad (1.2)$$

Given an RF wave of constant velocity ($C = V_o$) then we can re-arrange the Planck-Einstein relation of the speed of light (Equation 1.3) to find that the Doppler frequency (f_D in Hz) would equal two times[2] the velocity of the wave source over the wavelength of the source wave (1.4). The Doppler Shift would thereby be the difference between the Doppler frequency emitted and the Doppler Frequency received.

$$c = \lambda f \rightarrow f_o = \frac{c}{\lambda} \qquad (1.3)$$

$$f_D = \frac{2v_o}{\lambda} \qquad (1.4)$$

Where v_o is the velocity of the moving object (the flying bee)

[2] Because the Doppler shift affects the wave incident upon the target as well as the wave reflected back to the radar, the change in frequency observed by the radar due to a target moving at relative **Δ**v is twice that from the same target emitting a wave (Wolff, 2018)

Equation 1.4 is valid, however, is limited as the equation assumes the bee is only flying towards or away from the radar in a linear path. Therefore, the previous equations are justified only for the distance between the bee and the radar. Because the bees will fly in other directions in three-dimensional space, not only in a linear direction from the radar, the angle between the direction of the transmitted/reflected signal and the direction of the flight of the target must be accounted for ($cos\alpha$):

$$f_D = \frac{2v_o}{\lambda} cos\alpha \qquad (1.5)$$

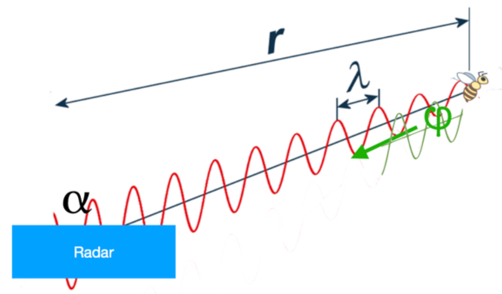

Fig.1.1b Phase Shifting of Receiving Signal

The phase shifting (φ) of the electromagnetic wave from the radar antenna to the aim (bee) and back results from the ratio of the covered distance over the wavelength of the transmitted energy multiplied by 2π (Equation 1.6). Knowing that the aim's velocity is equal to the derivative of radial speed over time (Equation 1.7) then the value of the phase changes through equations 1.8 to 1.9 to finally achieve the Doppler frequency (1.10).

$$\phi = \frac{(2r)(2\pi)}{\lambda} \qquad (1.6)$$

$$v_r = \frac{d(r)}{dt} \qquad (1.7)$$

φ = phase-difference between the transmitted and the received signal

2r = the distance: to object and back to radar

2π = 360°: the period of an oscillation

λ = wavelength of the transmitted energy

Then the value of the phase changes to:

$$\frac{d(\phi)}{dt} = \frac{-4\pi(V_r)}{\lambda} \qquad (1.8)$$

This is equivalent to the Doppler-frequency f_D according to:

$$f_D = \frac{1}{2\pi} * \frac{d(\phi)}{dt} = \frac{1}{2\pi} * \frac{-4\pi(V_r)}{\lambda} \qquad (1.9)$$

$$|f_D| = \frac{2(V_r)}{\lambda} = \frac{2(V_r)(f_o)}{c} \qquad (1.10)$$

(f_{tx})= is the radars frequency

(C_o)= is the speed of the electromagnetic wave

(V_r)= is the radial velocity of the aim

which, can be rewritten as:

$$f_D = \frac{2v_o}{c} f_o \qquad (1.11)$$

Knowing the change in frequency (Doppler frequency/shift) allows us to distinguish between orientation bees and foraging bees. The principle in deciphering between orientation bees and foraging bees lies in the knowledge that foraging bees fly out of the hive at faster velocities than orientation flight bees, therefore by using the Doppler shift equation orientation flight bees and forager bee's bodies emit different reflected frequencies.

At the moment, our Doppler radar algorithm weights the importance of forager bees and general activity frequencies about equally; however, future work with the device could allow for the device to be more selective of one bee type activity over the other, depending on which may be a better indicator of colony health. For the sake of this experiment however, activity between both types of bees were weighted as equally important factors in determining colony health.

One analysis method seeks to identify individual bees from a variation of signal strength at each frequency as a function of time. An alternative method seeks to quantify the total bee activity from the total energy of the return signal from all flying bees. The amplitude of this total return signal (A_m) is measured over time. The Root-Mean-Square (RMS) of this, the amplitude (equation 1.11) of the signal represents the overall activity of the hive[3] and therefore this calculation allows us to quantify the overall activity of the hive as shown by equation 1.12:

$$A(t) = A_m \frac{\sin(2\pi)(t)}{T} \quad where \quad \frac{(1)}{T} = f \qquad (1.12)$$

$$M = \frac{1}{T} \sqrt{\int_0^T A sin^2(2\pi f t) d(t)} \qquad (1.13)$$

[3] The root mean square of a quantity is the square root of the mean of the squared values of the quantity taken over an interval. This calculation allows us to quantify the overall activity of the hive and is represented by the equation 1.12.

1.3 Research Phases

In order to achieve the goal of validating the Doppler radar as a tool to measure colony health, three phases were taken as shown pictorially in Fig.1.2. In which Phase I was to verify that colony health can be measured through external bee activity from the hive entrance. Phase II was to determine whether the Doppler radar's RMS value was correctly measuring external bee activity. Phase III was correlating health to the Doppler radar RMS value.

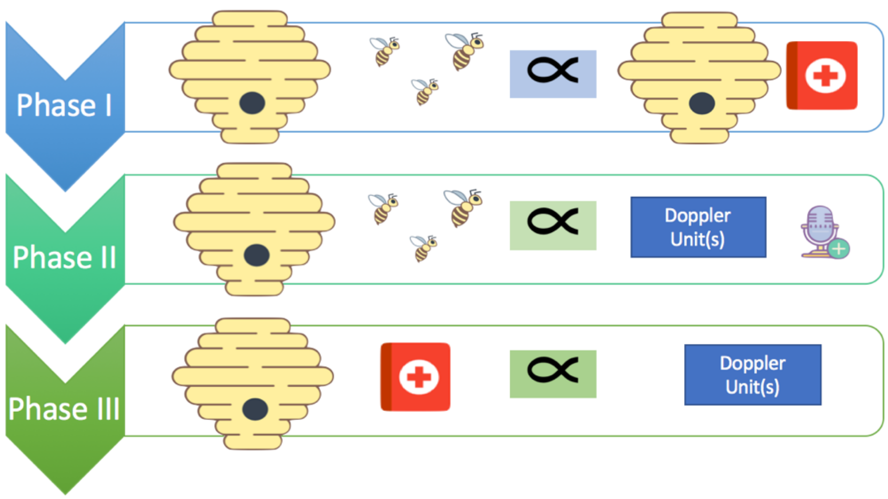

Figure 1.2. The three chronological phases of the research conducted to evaluate Doppler radar as a tool for measuring honey bee colony health.

CHAPTER TWO

PHASE I: BEE ACTIVTY VS. COLONY HEALTH

2.1 Phase I Methods

In Phase I, I worked to corroborate literature stating that bee activity is correlated to health of the colony. In order to determine whether colony health and honey bee activity were correlated, forager bee activity was monitored visually and recorded using a handheld clicker (see Appendix Fig A.3) and compared to the health status of each colony. Forager bee activity was chosen to be monitored over the general activity as it is more accurate for the observer to measure bees coming and going at high velocities than to count general activity. This is because orientation flight bees and guard bees' flight patterns are rapid and non-linear; therefore, counting individual bees demonstrating general activity is difficult with the human eye and will may result in redundancy in the data. The assumption made was that counting only forager bees manually and comparing to Colony Health values should not be much different than both forager bees and general activity compared to Colony Health as this study infers that general activity (McElroy, 2017) and forger bee activity (Frazier et al., 2015) are both related to the health of a hive (Appendix Figure A.2).

Manual counts of bees flying in and out were conducted on eleven hives. All measurements were taken between 1:00pm to 2:30pm, as the literature shows this is an active point of day for forager bees (Voeller, 2017). The duration of the count was 90 seconds long for each trial and there were six trails, 3 measuring bees flying in then 3 measuring bees flying out of the hive in a consecutive time frame. Total Bee Activity was the sum of the average of

“IN” and average of “OUT” bees. For “IN” bees, the bees were counted only if the bees fully entered the hive, as behaviorally, robbing bees from other hives are not 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. For “OUT” bees, foragers were counted. Determining forager “OUT” bees is distinguished by their behavior. Forager “OUT” bee behavior can be described as a rapid linear motion as the honey bee will “shoot out of the hive like a rocket” as it searches for nectar and pollen. Counts per day were averaged for all eleven hives and these counts were conducted during a one-week time span. Colony health was then determined afterwards, as it is known that opening hives affects hive activity and productivity for several days. Thus, to avoid this, colony health was evaluated after all activity measurements and the process of evaluating all eleven-colonies occurred over a time span of three days after the measurement of bee activity was recorded.

Defining colony health has been one of the most complicated questions in honey bee research. As honey bee colonies contain various complex relationships that are still under investigation, there are various methods in which honey bee health can be evaluated. The European Food Safety Authority (EFSA) created a panel on Animal Health and Welfare, AHAW, in 2016; in which, the mode of assessing health status of honey bee colonies was addressed. They identified a variety of key variables that are used commonly to asses and define colony health holistically. The consensus of the panel came to the notion that health is driven by various factors best illustrated by this conceptual model:

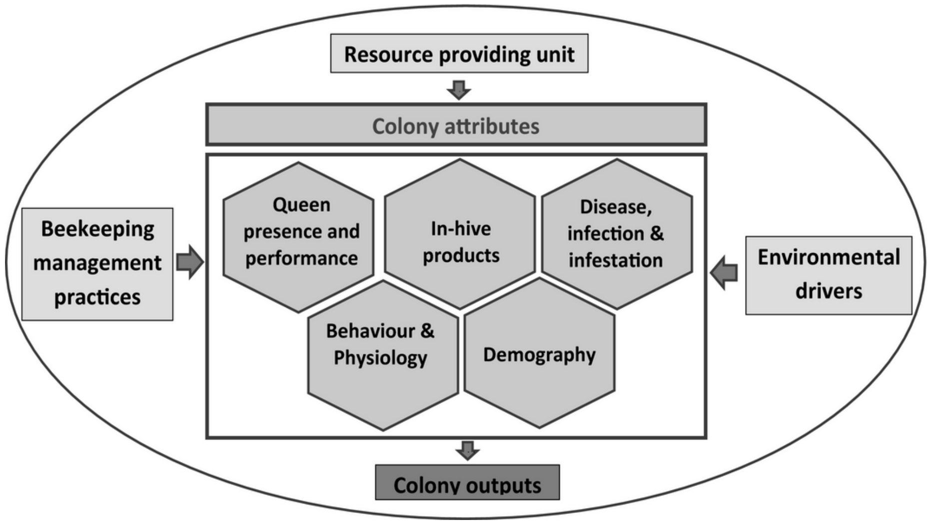

Figure. 2.1: Created by the EFSA panel in 2016. The diagrams show colony attributes (5-hexagonal structures), external drivers (Beekeeping management practices and environmental drivers) and colony outputs (honey, food pollination measured through crop yield) should be considered as a multidimensional assessment of the health of a managed honey bee colony.

The model demonstrates that the definition of colony health is comprised by various components, and thus could be measured by any combination of the hexagonal figures above. Of these colony attributes, honey bee queen presence and performance can be measured by observing honey bee larval numbers (brood size). Where "in-hive" products (such as honey) can be indirectly correlated to the number of worker bees, the philosophy being the more bees aiding in the production of in-hive products the more in-hive products there will be. Thus, the summation of worker bee population and brood population as population size of a colony is a strong indicator of colony health because it demonstrates the productivity of a colony; the consensus being that healthier hives are a product of a healthy queen who is laying more eggs thereby providing more worker bees who will collect more nectar to produce honey (Ostrofsky, 2015).

In order to measure population size, the number of capped brood[3] and workers per frame were estimated using a frame tool that was split into 2 quadrants, 8 sections, of 110cm^2 per section. Amount 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. Percent of workers and percent of brood per frame were then determined through equation 2.1 show below:

$$\left(\frac{(\text{Quadrants filled side 1 of frame})(110)+(\text{Quadrants filled on side 2 of frame})(110)}{\text{Area of oneside of the frame}*1759\text{cm}^2}\right)*200=\%\left(\frac{\text{workers}}{\text{frame}}\right) \qquad (2.1)$$

Total number of workers and total number of brood was then determined by frame size through the use of the equations 2.2 and 2.3 which were derived by Burgett (1985). Equation 2.2 is based off a frame size area of 1,759cm^2, a deep frame, and equation 2.3 based off a frame size of 1,820cm^2, a medium frame:

$$y = 0 + 12.15x \qquad (2.2)$$

$$y = 0 + 9.1x \qquad (2.3)$$

In this study eleven hives were observed at four locations in Orono, Maine. The use of farms in different locations ("demography") is an important factor to consider when assessing health of a hive. As some hives were placed in more resource advantageous locations these honey bees were able to expand to larger sizes and therefore assessing these

[3] 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.

hives allowed for a greater range of weak to strong colonies. Locations were labeled by either farm names or location of the apiary: Roger's Farm, Grove Street Extension, Collins Center, and Witter Farm. Hives were selected through preliminary observation of colony activity. Over all, there were 3 weak colonies, 4 moderate colonies and 4 strong colonies selected and observed.

2.2 Phase I Results

Figure 2.2 depicts the correlation between the average activity of forager bees coming IN and going OUT of the hive and colony health as represented by honey bee population size and has an r^2 value of approximately 0.48 ($p = 0.017$), meaning that foraging bee activity accounts for nearly half of the variation in colony health. This is not only an important validation of current literature, but also is an important validation of the purpose of the Doppler sensor, as it means that foraging bees play a large role in determining colony health and therefore are a viable source to be measured for colony health.

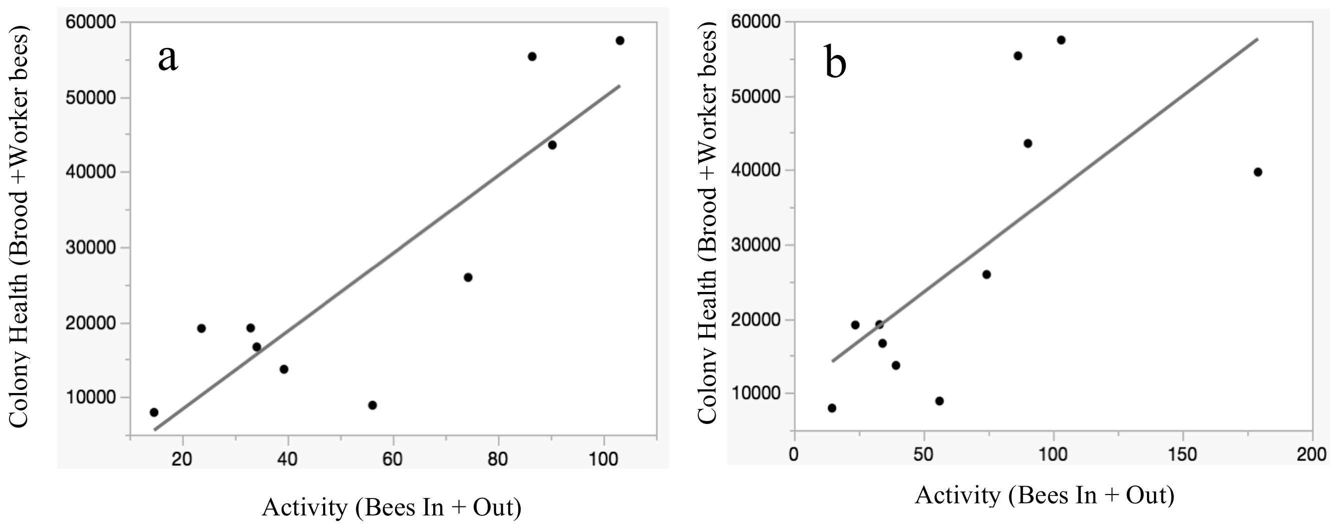

Figure 2.2a (left) and Fig.2.2b (right): These figures show bivariate fit of colony health by honey bee foraging activity. Phase I data collected from eleven hives at four locations. The r^2 statistic approaches 1.0 when hive H was excluded (Fig.2.2b for plot with hive H). Yet, the relationship remains strong even with this potential colony outlier point. This data provides evidence that activity of foragers is a good indicator for colony health.

The disparity in the data, between Fig.2.2a and Fig.2.2b, specifically the outlier point of colony H, most likely comes from the disparity of measuring activity and colony health on separate days. Weather conditions determine bee foraging activity. It is known that when there is less solar radiation and lower temperatures (a stronger chance of rain) bee foraging activity will decrease, and more bees will reside in the hive. Whereas, on hotter sunnier days, more bees will forage for pollen and nectar and therefore will not be in the hive (Drummond, 2016). Looking back through weather reports from a weather station which this laboratory had placed at one of the apiaries, I found that the average temperature on July 12th was higher than all the other days that I measured honey bee foraging activity (83^{o}F) and that solar radiation was also high on this day (peaking at 868.8 w/m^2). Therefore, colony H which was sampled on July 12th, had a very high average foraging activity and therefore explains why it appears to be an outlier compared to the other points that lie along the regression line.

With the inclusion of the colony H data point, the r^2 value was 0.48 and the p-value was 0.017, a significant value. After excluding the data point for colony H, based upon the justification previously mentioned, the adjusted r^2 value was 0.75 and the p-value was 0.001 thus indicating that colony health is strongly correlated to colony activity. In either case, the results from this phase suggest that colony health can be represented by honey bee foraging activity.

CHAPTER THREE

PHASE II: BEE ACTIVITY VS RMS

3.1 Phase II Methods

The purpose of Phase II was to see if the Doppler radar measured changes in honey bee foraging activity. In order to determine whether the Doppler sensor's RMS and honey bee foraging activity were correlated, forager bee activity was monitored visually and recorded using a handheld clicker (Appendix Figure A.3) and compared to the RMS values of the sensor for those measured times. Forager bee activity was chosen to be measured over general activity (i.e. orientation flights) as it is more accurate for the observer to measure bees coming and going at high velocities than to count the more random and less directional general activity. This is because orientation flight bees and guard bees' flight patterns are rapid and non-linear; in other words, counting individual bees demonstrating general activity is difficult with the human eye and can result in inaccurate data.

Six hives at the Grove Street Extension apiary (University of Maine) were observed in order to determine whether the Doppler's RMS values measured levels of honey bee activity that were specific to each colony. Six Doppler units were placed to collect RMS values of colony activity. Activity trials for these six hives were performed during set hours of the day, ranging from 8:00 am to 11:30 am, 12:00pm to 3:00pm, and 4:00pm to 8:00pm. Visual foraging activity measures were recorded exactly as described in Phase I. Each measure was 90 seconds long and repeated for 3 times as replicate measures of each colony.

For each of the 3 trails one "IN" measurements were taken followed by one "OUT" measurement per hive. Measurements were taken for at least three separate days per hive. Visual counts were time stamped and equivalent RMS values for the visually recorded count times were retrieved from the Doppler devices memory and analyzed through the use of MATLAB programming (code written by Dr. Emanetoglu). Counts and RMS values were averaged per day. Data was entered into Google Spreadsheets, plotted using Excel, and analyzed using linear regression with JMP statistical software.

Furthermore, visual counts of foragers were compared to a 10.5 GHz radar whose output was digitized as a WAV file. Using a MATLAB script (code written by Dr. Aumann) data was processed, and time-frequency-intensity plots were generated to show all individual forager bees flying at that time span (90 seconds of recording simultaneous to manual counts) as shown in Figure 3.1 These forager tracks were counted and averaged to correlate visual counts with radar frequencies taken over the same time span.

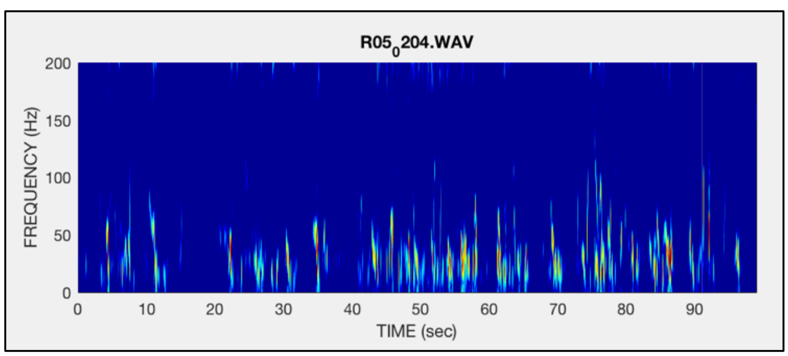

Figure 3.1. Time-frequency-intensity plot from the 10.5 GHz radar. This image shows that the frequency of forager bees are stronger peaks that approach 90-150Hz. Due to noise created by the device at lower battery power, lower frequencies were obscured and therefore only higher intensity (yellow/red) peaks were considered as forager bees. The noise from the hive itself can be noted in this recording and can be seen as the light marks at 200Hz.

3.2 Phase I Results

A. The 10.5 GHz Radar Verifies Manual Count Accuracy

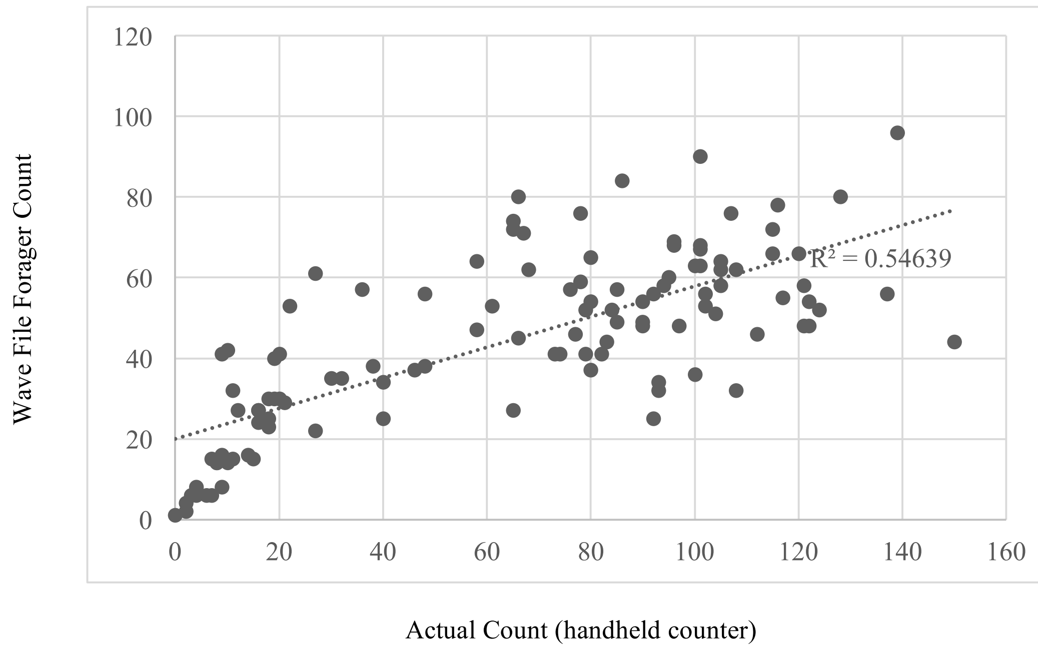

Figure 3.2 Wave file Doppler (10.5 GHz acoustic radar) tracts and the visual handheld clicker counts of honey bee foraging activity.

Figure 3.2 shows that the measured visual honey bee forager counts explained 55% (r^2 = 0.55, p = <0.0001) of the variance in Doppler tracks recorded from the 10.5 GHz radar. The 10.5 GHz radar is a low powered device that isn't overly sensitive to moderate levels of flying bees. However, it can become saturated with higher activity and physical interference of other factors, such as rain. Making this radar device suitable as a tool to verify that Doppler radar does correlate with visual honey bee foraging activity, but ill-suited for the field to measure overall bee activity (foraging + general activity). The device can pick up both general activity and the forager bee activity. The forager bees can be seen at the frequencies of 150 Hz and higher and the general activity are lower frequencies. A protocol to count only high intensity (red/yellow) and high frequency (150Hz) tracks insured that forager bees were in fact being counted and not noise[4]. Overall, 53% of variation explained in Doppler frequency measures is a strong indicator that visual counts of foragers were picked up by the Doppler unit. This paper has already clarified how the forager bees were distinguished from orientation flight bees whose flight path are smoother and more rounded in than that of the direct coming and going of forager bees. However, in distinguishing robbing bees this research states it observations that large attacks of robbing bees are distinguishable from forager bees, despite similar rapid flight patterns, in that robbing bees appear to be a darker color due to hair loss from abrasion with honey and guard bees. In which, the physical act of robbing altercation between honey carrying robbing bees and guard bees, causes the stripping of yellow setae from the abdomen of the robbing bee's body and makes them appear shiny and black (Storch, 1985).

B. RMS vs. Visual Counts

Six colonies were observed for both IN and OUT bee activity at the Grove Street Extension apiary. However, due to a malfunction in the real-time clock modules, only two units placed on hives #4 and #6 reliably recorded time-stamped data. The clocks on the four other units reset occasionally, making the time-stamp in the data files incorrect. The measurements from hives #4 and #6 were compared to the visual counts as shown in Fig.3.3 and Fig.3.4. Furthermore, a single data point from both hives 4 and 6 were excluded due to an anomaly in RMS counts that occurred at both hives at the same time, perhaps a spike

[4] One issue of using this device was the noise level recorded. The issue to this noise arose most likely from a simple problem: fluctuating battery power. Thus, a protocol was produced to provide an accurate measurement of forager bee activity as explained in the text.

in solar radiation flux or the possibility of some other larger organism increasing RMS values to an unusual peak[5].

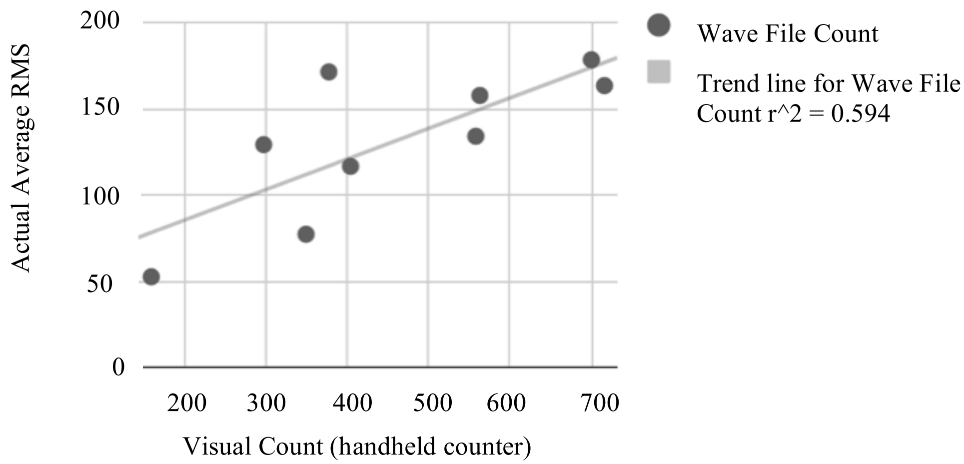

Figure. 3.3 Colony number 6 shows the regression between average visual counts and average Doppler RMS readings.

Figure 3.3 shows that the regression between average RMS and average visual counts have a r^2 of 0.594 ($p = 0.015$) which means that forager manual count explains approximately 60% of the variation in RMS count for hive 6. This signifies that the forager count and RMS values, which represent colony general activity, are closely related, thus the future of stating that RMS is good indicator of colony health is supported by this data.

[5] It is speculated that perhaps the anomaly was caused by a bumblebee passing directly over the sensor in attempts to steal honey while not flying in the direct path of the guarding honey bees.

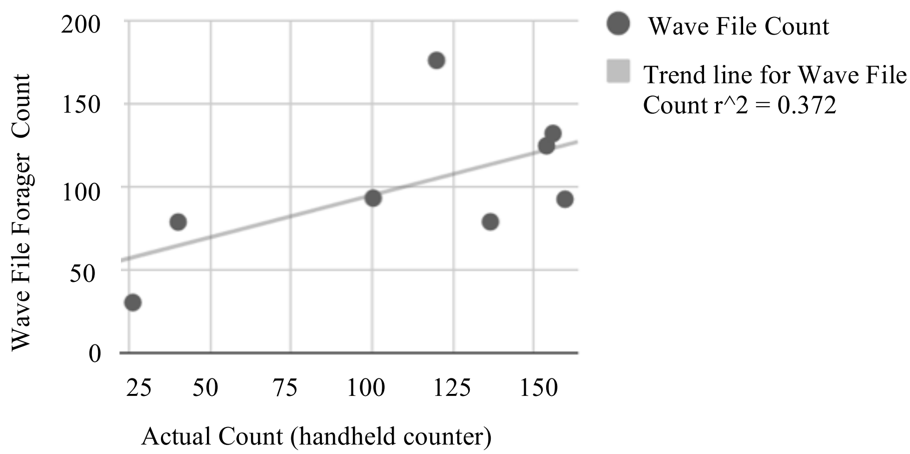

Figure. 3.4 Hive number 4 shows the regression between average visual counts and average Doppler RMS readings.

In Figure 3.4 the r^2 value for hive #4 is 0.372 (p = 0.126). In this case the regression, although still moderately strong, is weaker when compared to hive #6. The unexplained variation between visual counts and Doppler RMS in these hives might be due to general bee activity at the entrance being correlated to air temperature and solar radiation flux. As the temperature increases, more bees are found at the hive entrance demonstrating a wing fanning behavior that is for the purpose of forcing cool air into the hot hive[6]. The issue with this is that the Doppler radar measures the activity of the bees at the front of the hive fanning; which is not necessarily an indicator of colony health but is an indicator of how hot it is outside. Therefore, a spike results in the RMS values (Fig.3.4 and Fig.3.5) for colonies that have lots of general activity, but this spike in RMS is not necessarily indicative of orientation flight bees or forager bees. The question then is why this spike in RMS is not equally seen amongst all hives on a hot day? One possible answer could be that

[6] Fanning activity occurs most frequently in south facing hives (all hives were south except hive #5, which was North facing). The fanning insures proper ventilation, the survival of the brood, and the prevention of softening combs that if too soft would burst and release the stored honey (Storch, 1985).

the disparity between hives lies in the difference of general activity at the front of the hive on hot days due to the natural difference in ventilation between hives (due to orientation or holes within hive boxes) which would call for more or less bees at the front working to cool off the hive[7]. Therefore, due to these external factors acting upon the general activity at the front of the hive specifically due to fanning bees, it may be necessary to isolate and reduce the frequency noise of these bees that are simply fanning, and to perhaps focus the frequency range on the bees which are flying (specifically foragers). It can be seen in Figure 3.5 that on cloudy days, such as May 23, there are lower RMS peaks, and this is because there are less bees active in such weather. Whereas on hot and sunny days, such as May 21st, the RMS voltage peaks are much higher due to the increase bee activity. When looking at RMS vs avg. count of hive four (Fig.3.9) we see that the r^2 value is 0.37 and when we look at solar radiation vs RMS we see approximately the same number. This makes sense as general bee activity at the front of the hive is dependent on heat (solar energy).

[7] Other factors that might affect this are: the height of the hive (number of hive bodies), the orientation of the hive entrance to the sun, and the amount of brood in the hive, the major reason for controlling the internal hive environment

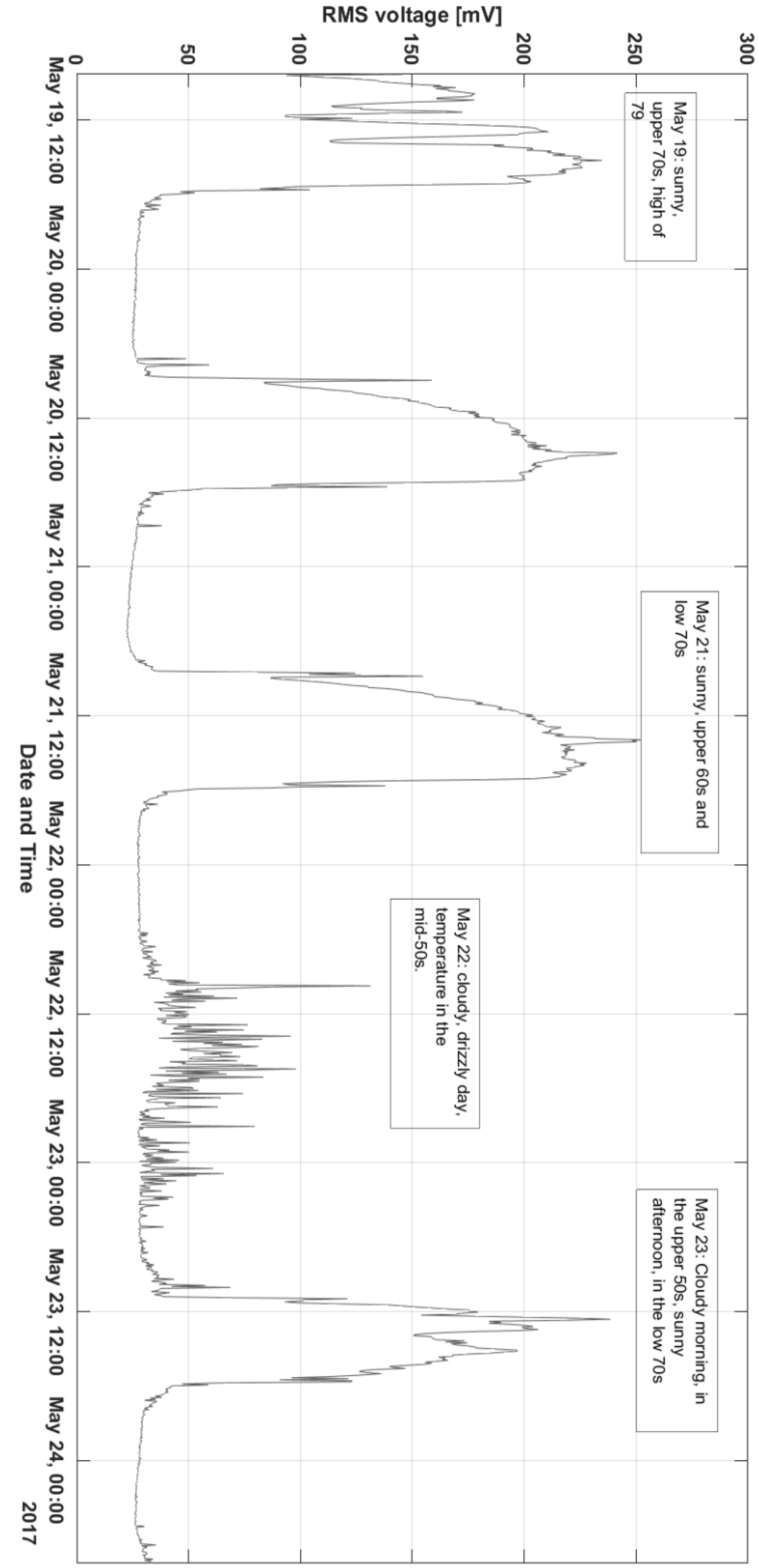

Fig.3.5 Data collected preliminary to research shows RMS voltage according to time with annotated weather notes.

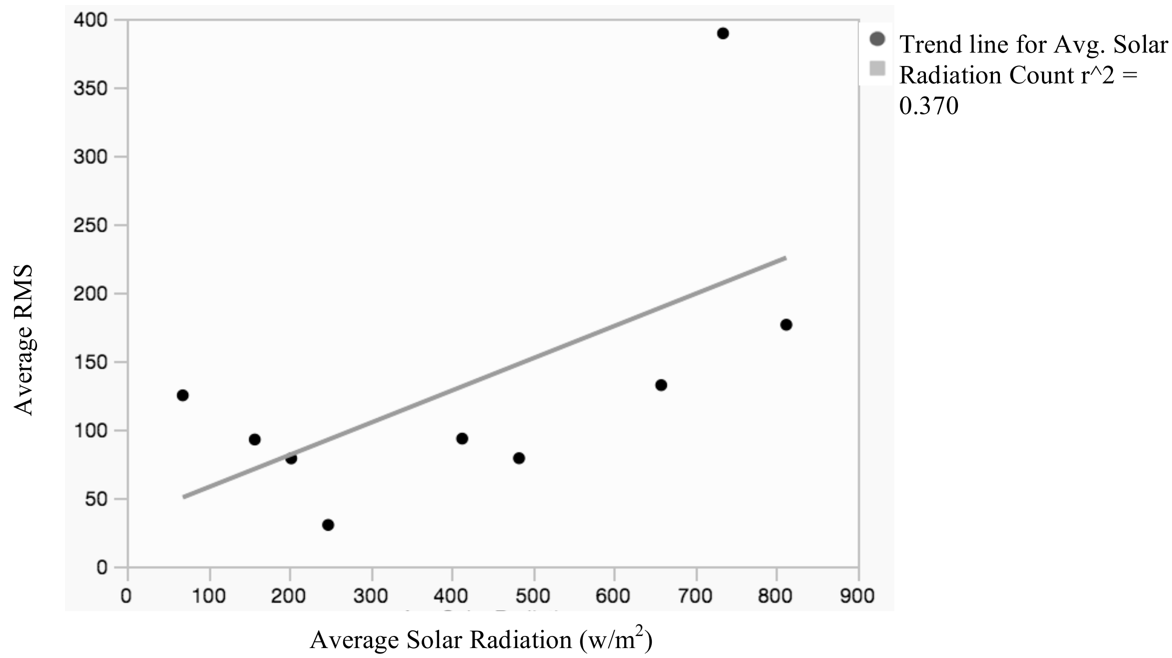

Fig.3.6 Data collected from Hive 4 in the Grove Street Extension apiary showing the relationship between solar radiation and Doppler RMS.

C. Daily Activity

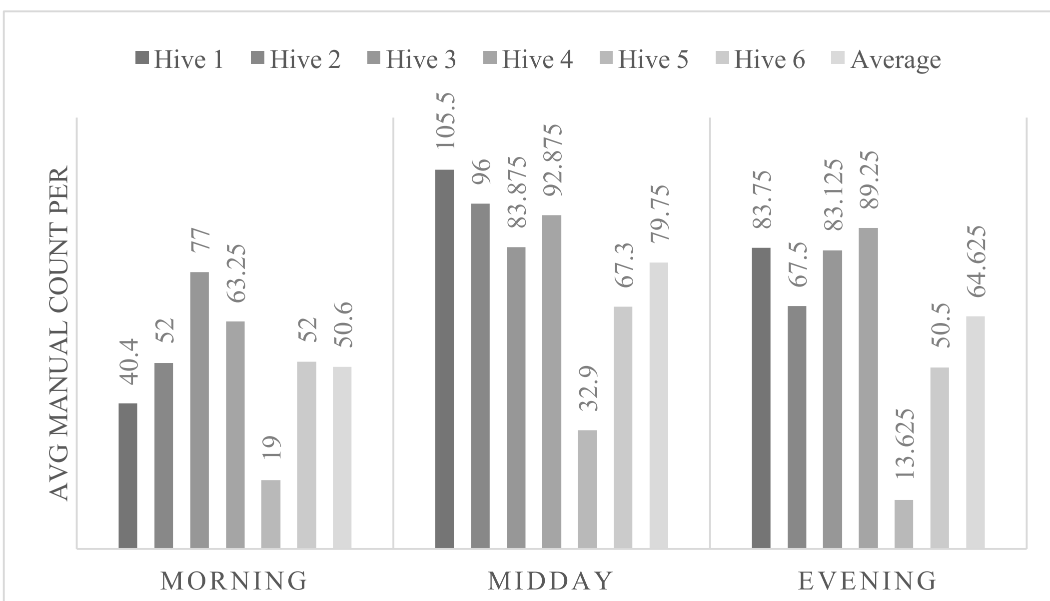

Figure. 3.7. Honey bee foraging activity throughout the day as measured by visual counts on six hives.

Results from my visual counts confirm that the most active times for forager bee flight is during the midday and evenings with the least amount of activity in the mornings (Fig. 3.7). This information is useful to see as it allows us to observe the variance in activity amongst the honey bees throughout the day and therefore RMS values should reflect this information. All hives, except Hive #5 were south facing hives. The information shown in Figure 3.7 was collected from the summer analysis of Phase I; where of the six hives only hives 4 and 6 held RMS values that correlated with the time frame of manual count data. However, manual count data was collected for all six hives and therefore can be used to determine the period during a day in which most hive entrance activity is seen. According to literature, the optimal temperature for honey bee foraging activity is between 16°C - 30°C and suboptimal conditions are that above 30°C, where foraging bees look to increase water collection over pollen and nectar collection (BC Ministry of Agriculture, 2015). At higher temperatures a healthy south facing hive[8] will therefore have lower foraging activity and higher general activity if temperatures rise above 30°C. However, for the state of Maine the average maximum temperature for June, July and August in 2017 were 25°C (U.S Climate Data, Updated 2018)[9]. Thus, even around midday, where temperatures are warmest due to the position of the suns direct rays, forager activity stays high during midday in the state of Maine. As hypothesized, Figure 3.7 supports the hypothesis that forager activity should be highest during the midday

[8] South facing hives are more likely to have fanning activity than other cardinal direction facing hives because these hive entrances have no protection against the direct rays of the sun. The benefit of having south facing hives is that the hive receives sunlight first and therefore the bees begin foraging earlier; while, the downside is that hive entrance will be much warming and prone to fanning bees aerating the hive. This may even appear to look like bearding but is not (Storch).

[9] Our weather recording station determined that the average daytime temperature (from 8am-8am) was 23°C for all three months of summer mentioned. Our weather station also recorded the hottest day of the summer was July 31st at approximately 3:00pm a temperature of 31°C.

period, followed by the evening and then morning. Because temperatures were also highest during midday, some fanning was observed at hives. Thus, from this data it can be concluded that the highest level of activity for both general and forager bee activity occurred during the midday period (12:00pm – 3:00pm). Therefore, this should be the optimal time to verify the Doppler radar with counts to make sure there is no over-saturation of signal to the device.

D. Intrinsic Error of Calculating IN/OUT Bees

Analyzing discrepancies amongst data points have led me to a better understanding of the procedure for validating the Doppler sensor. It has been observed that foraging honey bee activity is not equivalent for bees coming "IN" to bees coming "OUT" in a sequential pattern. It was assumed that bees coming "IN" would roughly equal bees coming "OUT" for a given time period. However, bees are quite complex organisms, and just as humans can stall before leaving home for a trip from in an overcast moment, so can a bee before flight out into the filed. Furthermore, some bees coming in and out do not follow a steady flowing stream like that of a river, but more like a set of cars at a traffic light. There will be moments where seven bees will exit after several minutes followed by a period of no forger OUT activity before the next batch of bees leave. Noting that these "batches" are not of consistent numbers; in other words, seven bees will leave, and then perhaps fifteen to twenty will leave. Meanwhile, it is possible that after taking several OUT measurements, the IN measurement that may follow will have many or no bees what so ever. Therefore, these gaps or bursts in bee activity could have resulted in a skew in the visual counts. The knowledge that bees do no fly in perfect sets (for example, 7 bees at a time entering/leaving) was known before hand, and thus attempts to avoid this statistical error came from multiple trials. However, as it became evident that these patterns became more variant with air temperature variation and solar radiation flux over time, it become less accurate to track bees in this manner.

Possible ways to avoid this issue were later discussed as either: more trials, staggering IN and OUT trials or for more precise measurements, and measurements done simultaneously by two individual counters. Therefore, in an effort for more data, the previously mentioned counting techniques were applied to a fall-season trial of four hives which were evaluated as an extension to Phase II and simultaneous to Phase III. In this experiment, four hives were evaluated with two individuals, myself and a partner (Berkay Payal).

E. Correcting Intrinsic Error of Calculation IN & OUT Bees through Simultaneous IN & OUT Counters

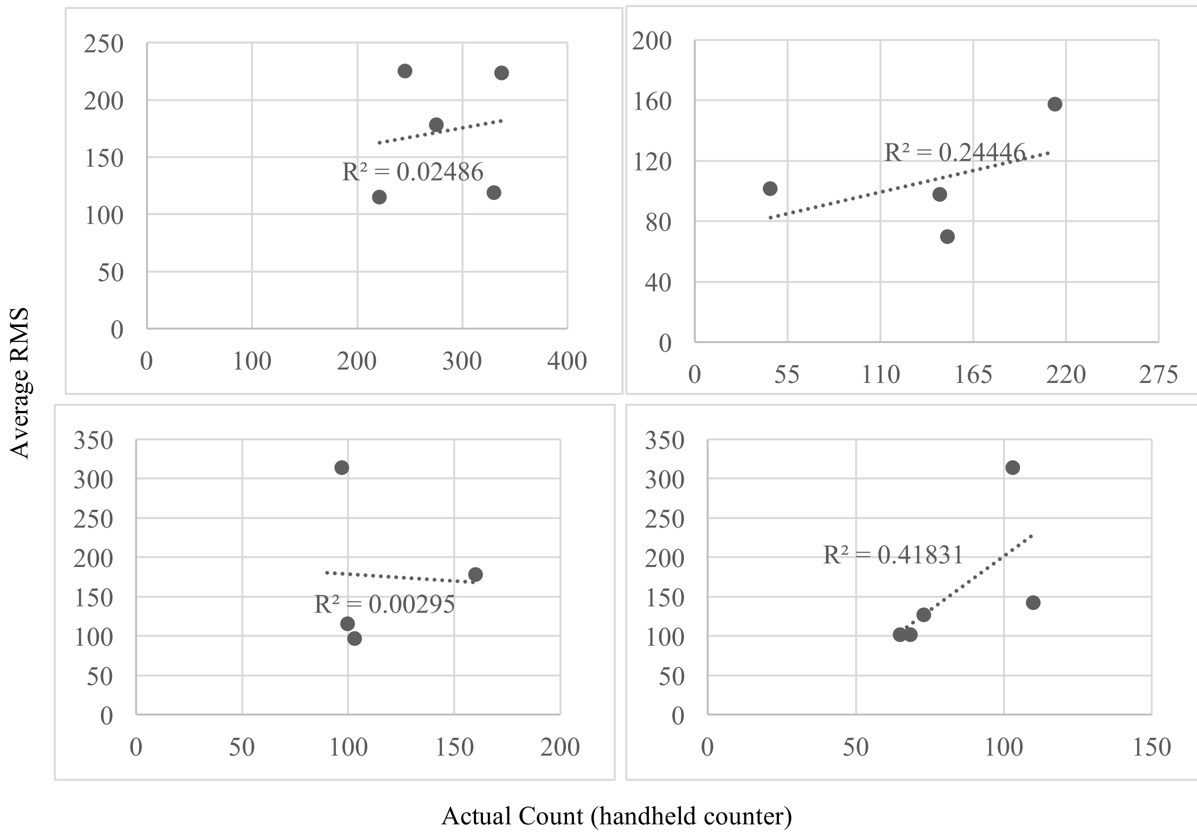

Figure. 3.8. From left to right, top to bottom, hives #1 (r^2 = 0.025, p = 0.80) , #2 (r^2 = 0.003, p = 0.945), #3 (r^2 = 0.245, p = 0.504), and #4[10] (r^2 = 0.418, p = 0.370). Here we see that Hives #1 and #2 visual counts of foragers contain weak regression relationships with average Doppler RMS.

As the results of the four-hives shown above (Fig.3.8) we can see that there are no strong positive regressions between visual counts and Doppler RMS. Only Hive #4 shows moderate correlations of r^2 of 0.42 (p=0.370), whereas all other R^2 values are below 0.1 (need to know the p values, see figure caption). All four hives were evaluated for at least five days; however, some RMS values were not found per trail. This error was speculated to stem from two plausible possibilities a) the error existed between the experimenters and

[10] Please note that Hive #4 in this study is the same hive as Hive #5 in Phase I, however, now in the fall instead of the summer.

the device. In this procedure the devices were turned on and off between each trial. As there is no indicating light for weather the device is on/off one cannot deny the possibility that: a) the experimenter could have mistaken the device to be recording when not, or b) The more likely choice that the device was not fully charged and therefore failed to collect data due to lack of power. The device does not have an indicator for battery life status and therefore if the device failed to charge the experimenter would not know. In commercial use, neither of these errors would occur with any frequency because the Doppler radar would continuously stay on within the field. Thus, the device would always be guaranteed solar radiation as a power source.

Furthermore, because data retrieval from the Doppler device can only occur within the laboratory (at this stage of the device development) it is not possible to determine if the Doppler unit functioned properly until it is removed from the field and taken to the laboratory.

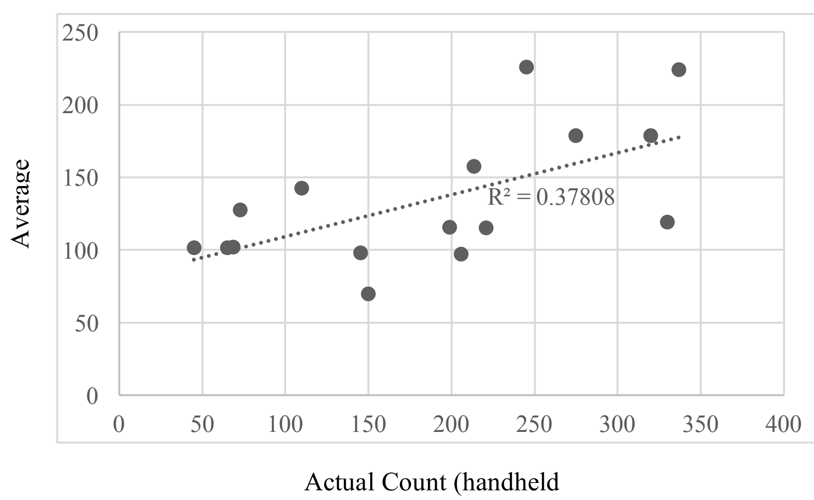

Fig.3.9. Note two outliers (high temperature/solar radiation averages) removed and now we can see that overall our activity was able to correlate activity and RMS weakly. The issue is just accuracy and ability to get enough data in one snapshot.

Thus, this left several hives with only four RMS readings. Individually this is not very accurate representation of RMS vs Activity. However, when placing all RMS data points vs RMS, we see a general trend between visual counts of honey bee foraging activity and Doppler RMS recordings (r^2 = 0.378, p = 0.052) as show in Figure 3.9. What can be concluded about this data is that visual counting is not the most accurate methodology of comparing RMS recordings and honey bee foraging activity without intensive continuous observation sampling (many more days). This can be very telling, as many beekeepers rely on visual observation to assess the strength of their hives. In other words, in order for a beekeeper who relies solely on their own visual observation of honey bee activity at the hive entrance to achieve an accurate representation of their hive's health, they would have to visit their hive for several consecutive days of observation and even then, could fall victim to misinformation about their hive's activity, and by consequence their hive's health due to the time of day (Fig.3.6) or weather (Fig.3.4).

Therefore, the Doppler device's ability to record data continuously allows for a more complete view of activity and therefore a more accurate representation of hive health. In regard to visual counts at the hive entrance, it can be concluded that with enough data, taken individually, or with the help of an additional person[11] focusing solely on the forager bees, an adequate measure of activity can be the result. The disparity seen in the correlations of manual counts and average RMS could come from the changing rates of

[11] This research would argue, from the results taken that this method was less effective than counting individually due to counter discrepancy. "Counter Discrepancy" is the discrepancy between human counters in determining what counts as "IN" and what counts as "OUT" between Phase IIA and Phase IIB.

general activity bees over time and forager bee activity over time. As discussed in section B of this Phase II, as weather data changes (Fig.3.4) the general activity changes even if the rate of forager bee does not (or do not change as dramatically, lagging in a transition period). The Doppler radar is able to record both forager bees and general bee activity simultaneously, whereas visual activity assessment only considering forager bee flux and therefore fail to accurately correlate strongly to the Doppler RMS (which includes both types of colony activity).

In addition to high air temperature and solar radiation increasing uncounted general activity for visual foraging activity counts, another issue arose with the visual count measurements: time of day. The experimental design was to make the visual counts during a time of day when high bee activity was expected. The literature suggests that this time is during the hottest time of day (See *Daily Activity*); or the time with the most sunlight (Egley, 2012). This was performed as a verification that the Doppler radar was not being oversaturated with signal due to high bee traffic. However, what was not calculated, was the oversaturation of the human eye. In hours of highest temperature which is about from 1-3 pm for the studied colonies (Fig.3.7) the highest levels of forager activity were measured. This activity could be accurately counted up until it reached over 200 bees in a 90 second interval, response time to stimuli was therefore not as accurate as it could have been in these high traffic hours.

F. Correcting Intrinsic Error of Calculating IN/OUT Bees through Continuous Data on Hive #3

Because of the previously stated error in averaging IN and OUT bee activity, counter discrepancy, and human counter saturation, for the six-hives evaluated over the summer, it can be more precise to simply inspect all IN and OUT data points non-averaged over the RMS values that correspond to their respective time stamps as shown in Figure 3.10. This representation is not only more precise in measuring the events occurring with bee activity and RMS measures at a given time but are also encouraging as it shows that there is in fact a general trend of declines and increases occurring synchronously between RMS values and the visual bee counts.

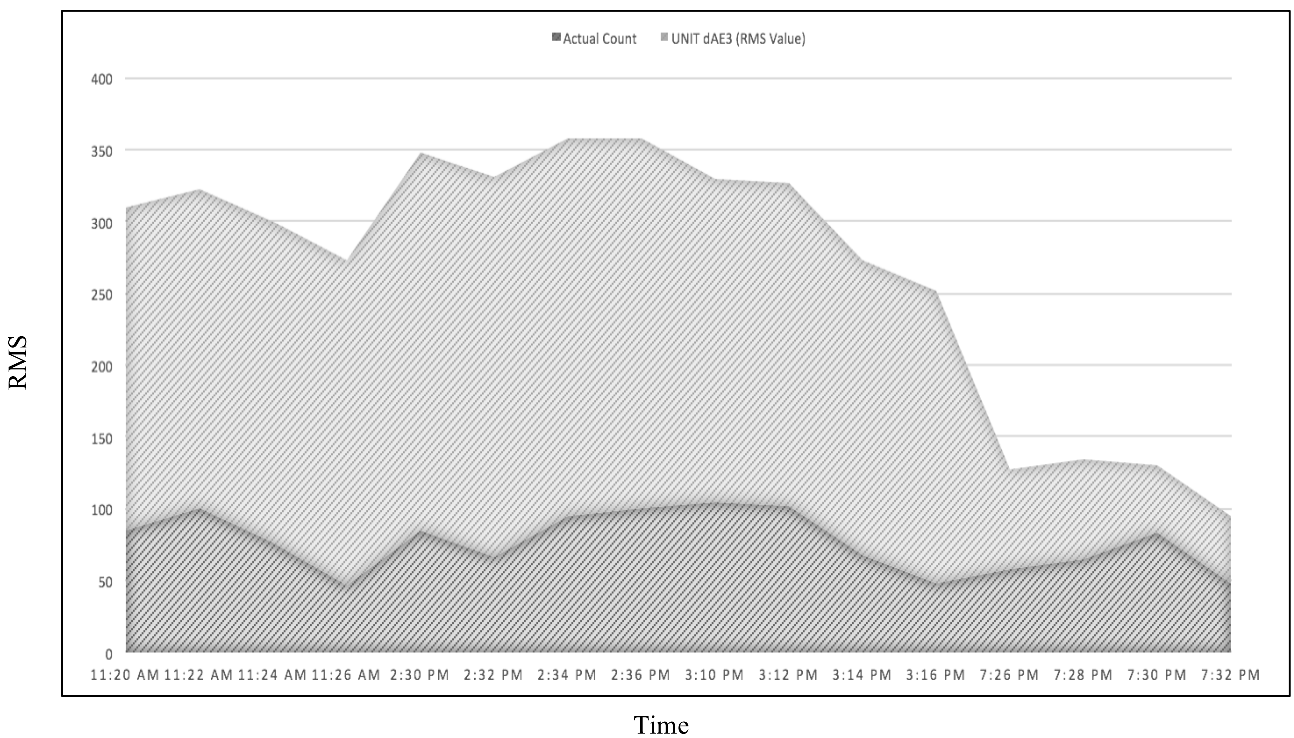

Fig 3.10 Trend of visual recorded foraging bee activity counts and Doppler RMS values over time for Hive 3. The y-axis is RMS, and the x-axis is time.

The data shown in Figure 3.11a and Figure 3.11b show similar peaks of activity at the exact times over several dates. Therefore, verifying that the Doppler radar was accurately measuring honey bee activity at the hive. There is a slight discrepancy on the third peak on August 3rd, where bee activity is lower and RMS greater in relation to August 2nd and July 30th. This is most likely because August 3rd had the highest mean temperature (of 23 °C) compared to the other two days (20 °C and 18°C respectively). This high temperature caused a greater number of fanning bees to stay at the hive entrance and are detected by the Doppler radar as activity. Therefore, a different device that would be able to pick up fanning bees only once– the moment they leave the hive to sit at the entrance– was needed. The answer to this process was the *BeeScan*® optic device and is discussed further in section *G*.

G. Using Continuous Data to Find Model of Effects for RMS on a Single Hive

Methods –The use of an optic sensor, although impractical for commercial use (as explained in the introduction), was valuable in the validation of the Doppler sensor's RMS as a measure of total bee activity. A single south facing hive from the Grove Street Extension apiary was chosen to be evaluated both with a Doppler radar and an optic sensor over the duration of several days. The optic sensor, *BeeScan*®, was used for this research and shown in Appendix Figure A.1 (July 27th to August 5th). It was installed at the hive entrance. The *BeeScan*® is comprised of a series of tunnels that sit in front of the hive entrance and allow the bees to access to the hive. Two lights per tunnel are positioned such that a bee crawling through a tunnel breaks the light beams in a specific order dependent upon whether the bee is entering the hive or leaving the hive. Depending on which beam of light was broken first as the bee’s body passed through the tunnel, allows the direction with which the bee flew (IN vs OUT of hive entrance) to be recorded. More importantly, the optic sensor design, being the only gateway of the hive, allows for a closer representation of RMS values as the optic sensor will measure all bees going IN and OUT.

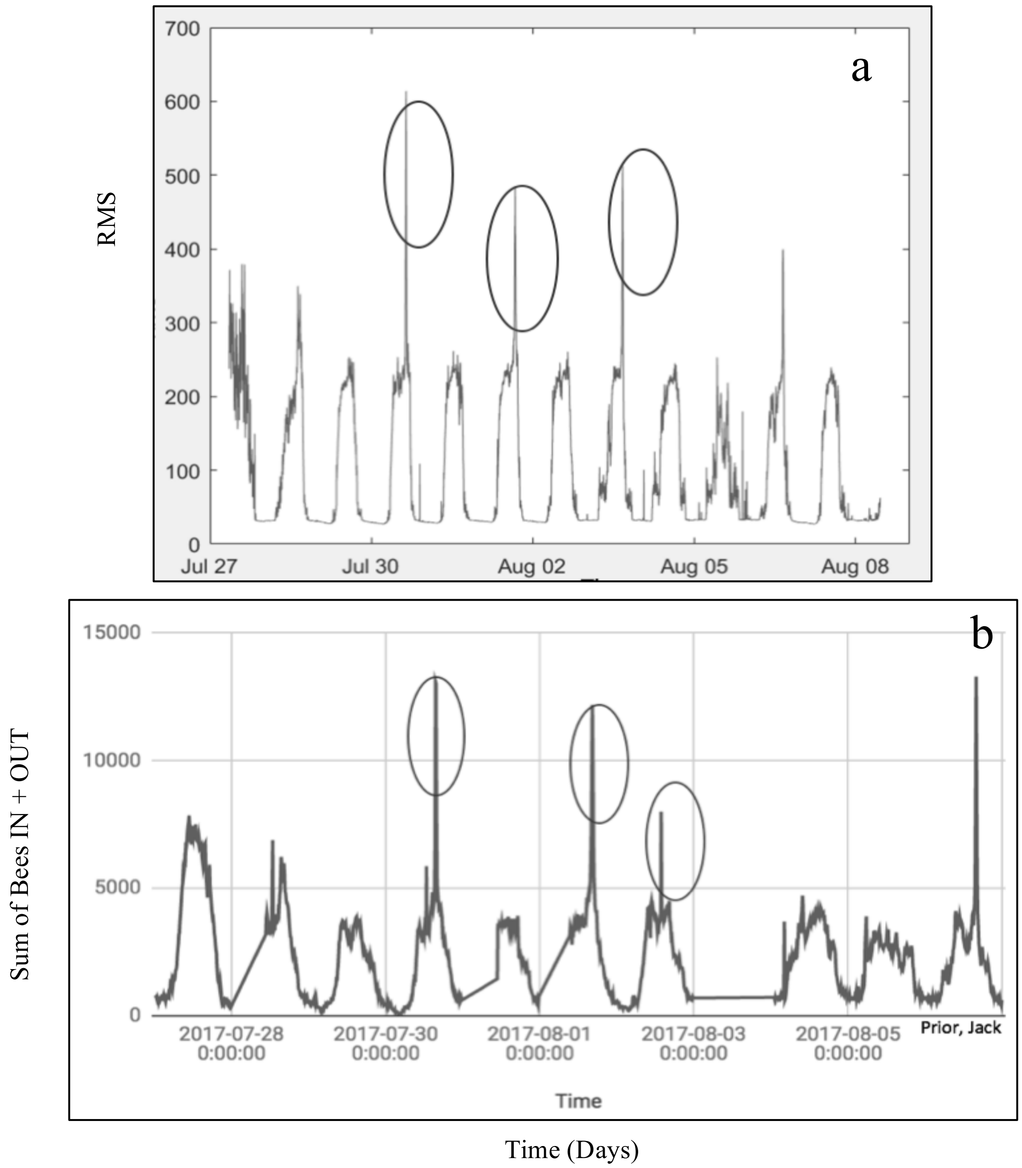

Figure 3.11. (a) Doppler RMS over time, 27 July – 8 August 2017 and (b). the sum of In and Out honey bees recorded by the *BeeScan*® optic sensor over time, 27 July – 5 August Circled peaks match with dates of peaks showing that Doppler RMS corresponds relatively well to bee activity recorded by the optic sensor.

Results - Figure 3.11a shows the recording of the Doppler Radar's RMS over time for a series of eight days (July 27^{th} to August 8^{th}) and Figure 3.11b shows the optic sensor's sum of bees IN+OUT over time. Because the *BeeScan*® optic sensor's counts of honey bee activity were similar to the Doppler RMS measures over time (Figs. 3.11a and b), this study then attempted to statistically model the extent that Doppler RMS as a proxy for bee activity is explained by honey bee foraging activity based upon the *BeeScan*® optic sensor and weather.

Methods - Using the JMP® statistical software package and the continuous data (shown graphically Figs.3.11a and b) from the *BeeScan*® optical sensor, a model to best quantify factors that affect Doppler RMS was developed. The Doppler Rader and *BeeScan*® optic sensor measured activity at different time frames. The *BeeScan*® measured data every ten minutes and the Doppler Radar every 5 minutes. Therefore, in order to achieve an RMS value for every *BeeScan*® activity point, all RMS values within the ten-minute span were averaged. Weather data was taken from a weather station that was set up in the same apiary as the hive monitored. (Dr. Aumann). Doppler internal relative humidity and internal air temperature was measured with sensors inside the Doppler Radar (prototype 1) and was initially hypothesized to be similar to the hive because the unit itself is a box exposed to the heat of the environment, much like the hive, these two measurements served to give insight on what the internal temperature and internal relative humidity of the hive was at any point in time.

Results – The best multiple regression model found for predicting RMS across the data time frame was assessed. It was concluded that the best fit model (Table 3.1) had the parameters of: day, external temperature, solar radiation and bee count and the reason for exclusion of the parameters of internal humidity, external humidity, and internal temperature are explained in these results.

Table 3.1 Predictive model for Doppler RMS across all days 7-27-17 through 8-05-17: Day, Average Internal Temperature, Internal Humidity, (External) Temperature, (External) Humidity, Solar Radiation.

	Source	**DF**	**Sums of Squares**	**F Ratio**	**Scaled Estimate**
Overall	Model***	39	8665589.8	211.52	
	Error	1157	1215413.3		
$r^2 = 0.873$					
Effects					
	Day ***	9	83243.7	8.81	
	Bee count***	1	1103856.2	1050.80	237.2
	Outside temperature***	1	61575.8	58.62	-10.85
	Solar radiation***	1	296458.2	282.21	47.86
	Bee count x Day***	9	182946.7	19.35	
	Outside temp x Day***	9	68417.9	7.24	
	Solar radiation x Day***	9	146511.5	15.497	

0.02 less than 0.05= * or less than 0.01 =** and then less than .0001 = *** greater than .05 = N/S

The model that explained the highest proportion of variation in RMS (estimated by the adjusted r^2) was a model where internal temperature and internal humidity were excluded (Model 4, Table 3.1). This support of the null hypothesis was contradictory to what I had expected (that internal temperature and internal humidity would have an effect of RMS). Based upon this, the new hypotheses to why these predictors are not important are that: 1) Internal temperature and internal humidity of the Doppler Radar are not reflective of the hive's internal temperature and internal humidity and therefore *should not* affect RMS; 2) the measuring components of the Doppler Radar are resistant to the extremes of internal temperature and internal humidity within the sensor during Maine summers (*See Section*

I); and 3) internal temperature and internal humidity are correlated to the outside measures of external temperature and external humidity.

The third of hypothesis above is tested through a modeling analysis involving all days and using all four previously mentioned factors plus internal temperature and internal humidity. At first glance, this model (Appendix Table A.1) seems valid with an adjusted r^2 of 0.94 and P values of parameters below 0.05. However, on closer examination the correlation of estimates demonstrates the inaccuracy of this model. According to the correlation of estimates, shown in Appendix Table A.5, air temperature and air relative humidity are strongly positively correlated $r = 0.71$ ($P = <0.0001$), meaning that external air relative humidity is a redundant parameter within this model. Furthermore, internal temperature and internal relative humidity are moderately negatively correlated $r = -0.54$ ($p = <0.0001$).

These statistics demonstrate that a more simple and clear to interpret model would be one without external relative humidity, internal relative humidity and internal temperature. In an analysis where internal humidity and internal temperature were removed, but not external relative humidity, as shown below (Table 3.2), it was observed that external temperature ($p = 0.144$) and external humidity ($p = 0.581$) are not significant predictors of RMS. Therefore, furthering the need to exclude external relative humidity, the least significant predictor from the model and refit the model.

Table 3.2. Model 2: Predicting variables which attribute to RMS across all days 7-27-17 through 8-05-17: Day, Average (External) Temperature, (External) Humidity, Solar Radiation; Excluding Internal Temperature, Internal Humidity.

	Source	DF	Sums of Squares	F Ratio	Prob > F
Overall	Model	13	8287995.5	473.4488	<0.0001
	Error	1183	1593007.7		
$r^2 = 0.837$					
Effects					
	Day	9	34536.7	2.8497	0.0025
	Bee count	1	2045025.9	1518.678	<0.0001
	Outside temperature	1	2879.6	2.1384	0.1439
	Solar radiation	1	461439.0	342.6740	<0.0001
	Humidity	1	403.8	0.299	0.5841

Once all three redundant parameters are removed, the refitted model proves to be the best fit model (Table 3.2). In this model, the adjusted r^2 of 0.84 is exceptionally high for a biological model and demonstrates that honey bee activity count, external temperature and solar radiation, explains 84% of the variation in Doppler RMS and under Analysis of Variance we see that this model is significantly predicting the dependent variable (RMS) with an overall model Probability (F) of less than 0.0001. Meaning that there is 1 chance in 1000 that the predicted RMS is the same as a null model of zero. This low value tells us that the independent variables are not purely random with respect to the dependent variable and that the variables hold significant value to determining Doppler RMS.

According to the correlation of estimates, shown in the Appendix Table A.6 this model shows that none of the weather predictors are strongly correlated for bee count, outside temperature, and solar radiation. Therefore, there are no autocorrelations in predicting parameters responsible for Doppler RMS. The estimates were also then scaled through JMP in order to predict which parameters held more importance. As seen in Table 3.1, the *Scaled Estimates*, we see that the ranking of importance of the weather parameters that determine RMS, from greatest to least, as: bee count ($p < 0.0001$), solar radiation ($p < 0.0001$), and then external temperature ($p = 0.009$).

We can also see how two parameters acting as one affect the Doppler RMS. For example, if we assess the interaction between day and bee count we are exploring whether the effect of bee count and solar radiation on Doppler RMS change from day to day. In the effects test of all given parameters we see that day crossed with bee count, temperature, and solar radiation are all significant in determining RMS. Therefore, this model tells us that the predictive effect of each one of these variables (Bee Count, Outside Temp, and Solar Radiation) is significant but the relationship between these variables changes from day to day. In other words, for some days there might be more activity for a given temperature and for other days at the same given temperature, the activity is different. For changes in foraging bee activity, the meaning of these variable interactions is indictive of changes in the amount of resources (flowers) or that the bee population of the colony is changing over time. Thereby affecting bee activity and in turn affect RMS, which is the principle hypothesis to the change in activity shown by the Doppler radar (Table 3.3).

Table 3.3 Effect Tests for source values showing the interaction effects with days.

Source	**Nparm**	**DF**	**Sum of Squares**	**F Ratio**	**Prob > F**
Day	9	9	83243.7	8.8048	<.0001*
Bee Count	1	1	1103856.2	1050.804	<.0001*
Outside Temp	1	1	61575.8	58.6165	<.0001*
Solar Radiation	1	1	296458.2	282.2103	<.0001*
Bee Count*Day	9	9	182946.7	19.3505	<.0001*
Outside Temp*Day	9	9	68417.9	7.2366	<.0001*
Solar Radiation*Day	9	9	146511.5	15.4967	<.0001*

H. Methods of Internal Temperature Effects on Doppler Radar Accuracy

In order to measure whether temperature was affecting the internal components of the Doppler radar a secondary experiment was run on the radar. A DC power supply was attached to a 6-volt DC motor with a revolving paper propeller that simulated the mechanical movement of a bee in a constant location within the air. A 75-watt lamp was then placed at varying increments from the Doppler device: about 12 inches, 6 inches, 3 inches, and one 1 (overhead) the device. The increasing proximity of the lamp near the device was purposeful in simulating an increase in temperature. The null hypothesis was that the RMS value was not affected by temperature. The alternative hypothesis was that RMS is not constant as temperature fluctuates. There were two prototypes tested: Prototype 1 (older) and Prototype 2 (newer design).

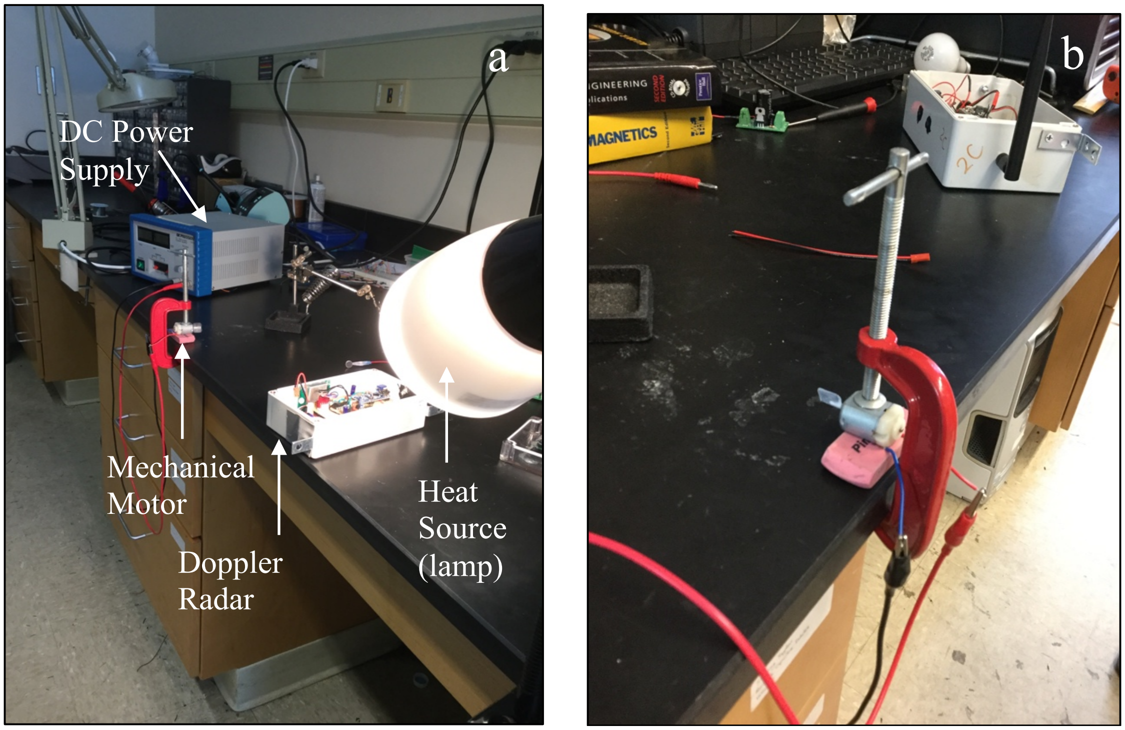

Figure 3.12. Demonstration of the set-up for the Doppler radar temperature effects experiment. To the left, the image shown is the entire experimental set-up with its labeled components (a). To the right, the image shown is a zoomed in photo of mechanical motor mechanism, showing electronic motor with paper flag attached (b).

I. Results of Internal Temperature vs RMS of Doppler Radar

As the figures 3.13a and b shows below, prototype 1 followed the alternative hypothesis. It was seen for this device, that internal temperature of the device has an effect on the RMS reading. The effect causes the readings to be inaccurate but in proportion (holding high precision) to bee activity fluctuations. Therefore, our assumption is that the data collected with prototype 1 is proportionally correct because bee activity is also a linear function of increasing air temperature and can be continued to be evaluated as if internal temperature was not significant. Nevertheless, moving forward in the Doppler Sensor design, Prototype 2's data is supported by the null hypothesis, therefore proves to be highly accurate as well as highly precise. Deeming Prototype 2 as the future for the Doppler Radar design.

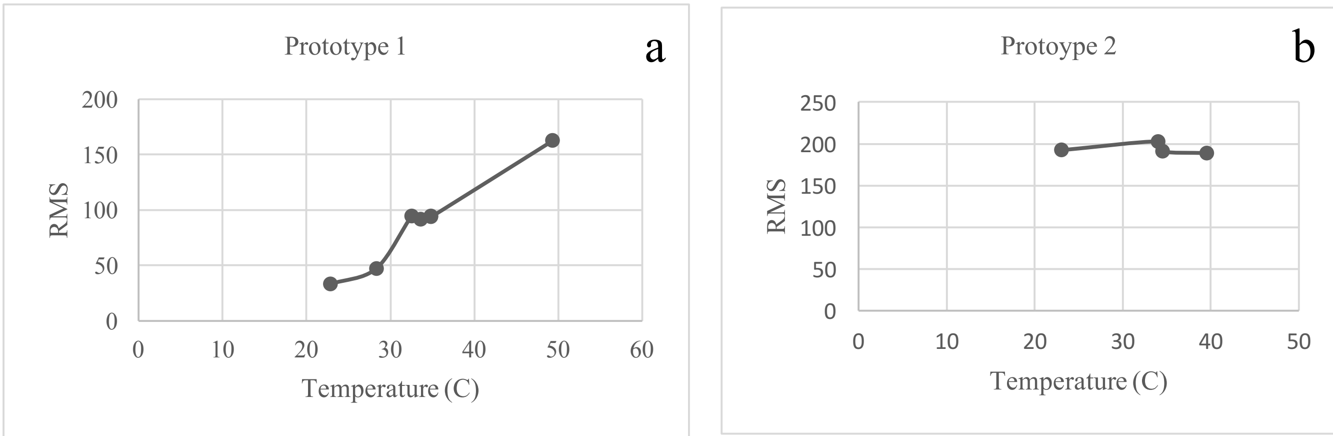

Fig. 3.13. Effect of increasing temperature on the Doppler radar, prototype 1 (a) and prototype 2 (b).

The problem with the temperature sensitivity is due to the analog-to-digital conversion, more specifically the reference voltage. An analog-to-digital converts an analog voltage (the Doppler signal in this case) to a digital number that a computer can process. Prototype 1's ADC is connected to a 5V supply voltage, which is a switching power supply type known as a boost converter. It converts the 3.7V battery voltage to 5V. It does this by switching on and off a current through an inductor and capacitor network. It is an inherently noisy mechanism. We use capacitors between the power supply line and ground to minimize this noise. Prototype 2's ADC is also connected to the supply voltage. However, in this case it is a 3.3V linear voltage regulator that converts the 3.7 V battery voltage to 3.3V. A linear voltage regulator does not cause noise as a switching power supply does.

When student and colleague, Mr. Berkay Payal, and I conducted further experiments to understand the problem, it turned out that the noise at the output of the amplifier, while not temperature independent, was much more stable. However, the noise at the output of the 5V switching power supply on Prototype 1 nearly tripled, while the noise of the linear power supply in Prototype 2 was much more stable (see Appendix Fig.A.4 and Fig.A.5 for basic schematics of Prototype 1 and 2). The additional noise on Prototype 1's power supply is what caused the problem, as the analog-to-digital converter (ADC) compares the voltage to be measured to the reference voltage (the power supply in this case). When the reference voltage is noisy, the measurement is noisy as well, even if the input voltage is an ideal constant voltage.

CHAPTER FOUR

PHASE III: BEE HEALTH VS. RMS

4.1 Phase III Methods

Four hives from September 13th to the 27th were evaluated between 1:00-2:00 pm. Three consecutive 90-second intervals where RMS recording were taken and then averaged for that time period. Recordings were taken for 5-6 days within a one-week span before health of hives were assessed within the following week. Colony health was assessed in the same manner as Phase I, however, because all colonies were evaluated within the same day the ratio of total estimated number of brood to total estimated number of workers was evaluated as a more accurate marker of future colony health per hive relative to the sum of worker bees and sealed brood (total colony population abundance).

4.2 Phase III Results

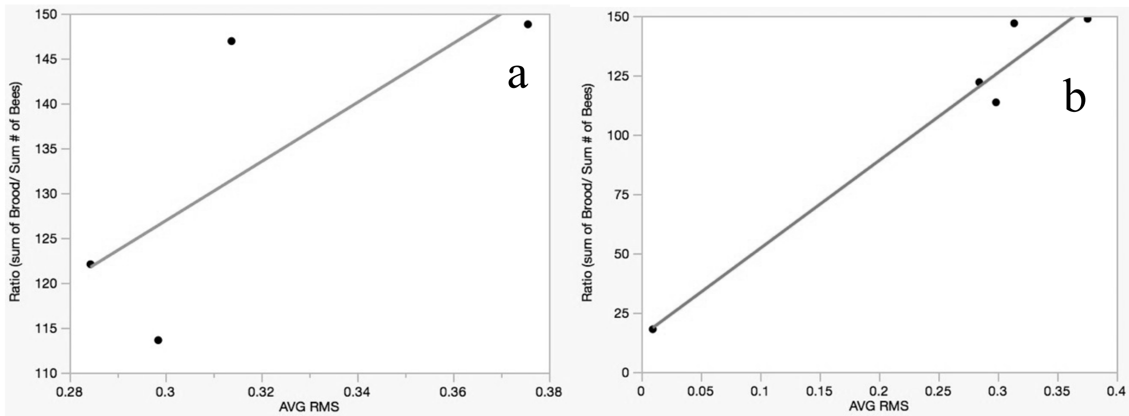

Figure 4.1 Relationship of average Doppler RMS and colony health given as a ratio for 4 hives measured in 2017 (a) and relationship of average Doppler RMS and colony health given as a ratio for 5 hives measured in 2017, including hive 7 (b).

Figure 4.1, demonstrates that from the four-hives evaluated in the fall of 2017, the RMS and colony health is not a significant linear relationship ($p = 0.25$). During Phase I and II, one of the hives (known as Hive #7) which did not have visual counts coinciding with RMS recordings was omitted from Phase II due to lack of coinciding data however used in Phase I for colony health. However, having both RMS and colony health assessment data assessed under similar weather conditions (26C and partly cloudy) allows Hive 7 to be placed within Phase III data set. Once the Hive 7 data was incorporated into the data set, we see that the relationship between average RMS and colony health is significant (r^2 = 0.96, $p = 0.003$, Fig 4.1b) as shown in Figure 4.1b.

CHAPTER FIVE

CONCLUSION

5.1 Concluding Thoughts and Future Research

Promising future research would be to expand my research in the Phase III part of my research study. Due to the experimental nature of the devices themselves, which during the summer when I was doing my research, were still being developed and fine-tuned by the Emanetoglu laboratory, there was not ample time to have the devices on other farms. Now that the prototype design has been remodeled to a newer, second, version it would be beneficial to study colony health and predict it using RMS of several more hives from various farms in order to achieve a variety of colony population sizes (such as was done with Phase I). In addition to this, an interesting study for Phase II could be determining how the Doppler radar measures colony health through activity changes when colonies are infected with parasitic mites (such as *Varroa* mites).

It has been documented in the published literature that both honey bee general and forager activity are important signs of colony health. From Phase I, this study found evidence to support this claim (Appendix 1.3). However, because of my small sample size, replicative studies are needed to assure that forager bees are not a better indicator of health colony than general colony activity and vice versa. Furthermore, because this study found that weather is a strong indicator of general activity and forager activity it would be interesting to pursue the behavioral differences of general activity vs. forager activity due to weather changes. Do forager and general activity fluctuate proportionally due to a change in weather? Does one decrease more rapidly than the other and if so how does this affect their correlation with colony health? If general activity and forager activity fluctuate similarly across a range of weather conditions, then there would be no need to modify the frequency range of the Doppler radar. However, if they differ independently (more one than the other) than there could be would be reason to change the frequency range of the Doppler radar to the variable that better predicts honey bee colony health. Furthermore, the use of the device around honey bees is considered safe due to the low power emitted by the device, which is lower than that of a Wi-Fi router. Nevertheless, a future study that researches whether long-term use of the Doppler radar with a colony is detrimental to its health should be conducted.

Mechanical upgrades of the Doppler radar could make the device more user-friendly in and out of the field. For example, one update that would make the Doppler radar device better would be the ability to connect the device to Wi-Fi so that someone can check on the status of the hives at any time within an appropriate reception range. In addition, a light on the device to indicate battery level and a light or label to indicate whether the device is on or off when in the field would prevent the likelihood of malfunction in the field going not noticed for extended periods of time.

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APPENDIX

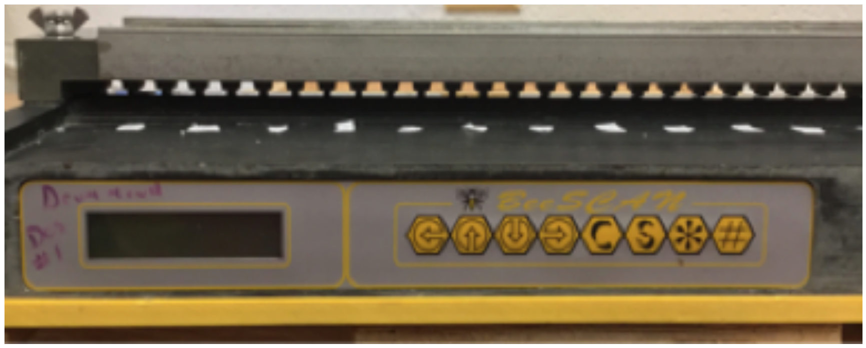
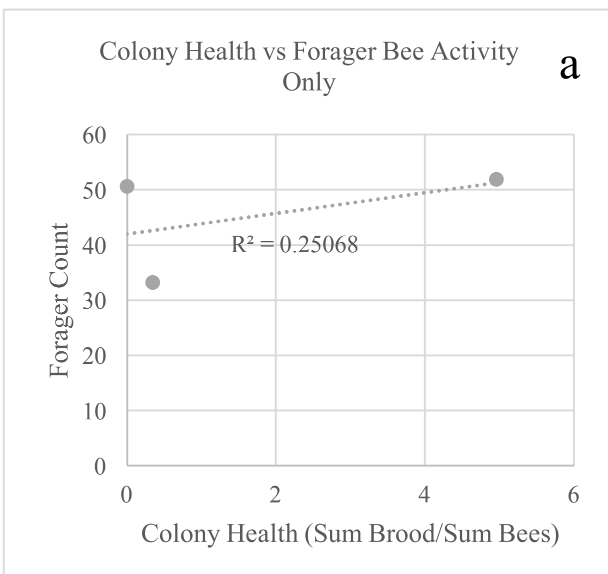


Figure A.1 *BeeScan*® technology uses two optical sensors per channel which thus allows for the counting of bees coming into or traveling out of the hive depending on which column of light is broken first.



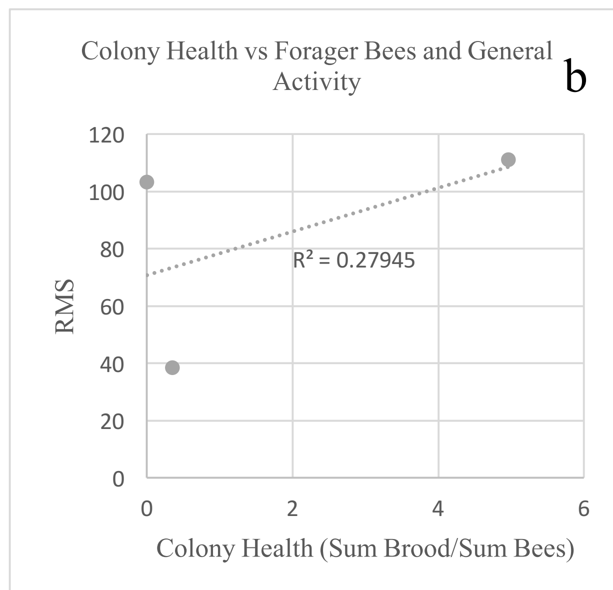


Figure A.2 Summary: This preliminary data taken from the first weeks of Phase II shows two figures. On the left, the data shows Colony Health measured by Sum of Brood/Sum of bees over Forager count determined through the 10.5 GHz radar (a). The figure to the right [due to the success of Phase II correlating bee activity and RMS] suggests that including general activity as well as forager bee activity, which is what the Doppler radar within this study measures, is more reliable in determining Colony Health than forager bees alone (data taken through the use of 10.5 GHz device). The statistical evidence is not enough within these models for this data to confirm correlation, however the general trend and the literature cited written by many beekeepers has confirmed that general activity at the hive plays just an important role as the foragers in determining hive strength (b).

Figure A.3. Manual (handheld) Counter (Phase II) (a). Audio Recorder Unit: Roland R05 used to measure Forager Tracks (Phase II) (b). Camera: Olympus Stylus 1010; 10.1 Megapixel (possible data collected for future analysis) (c). Doppler Unit- Prototype One (all phases) (d).

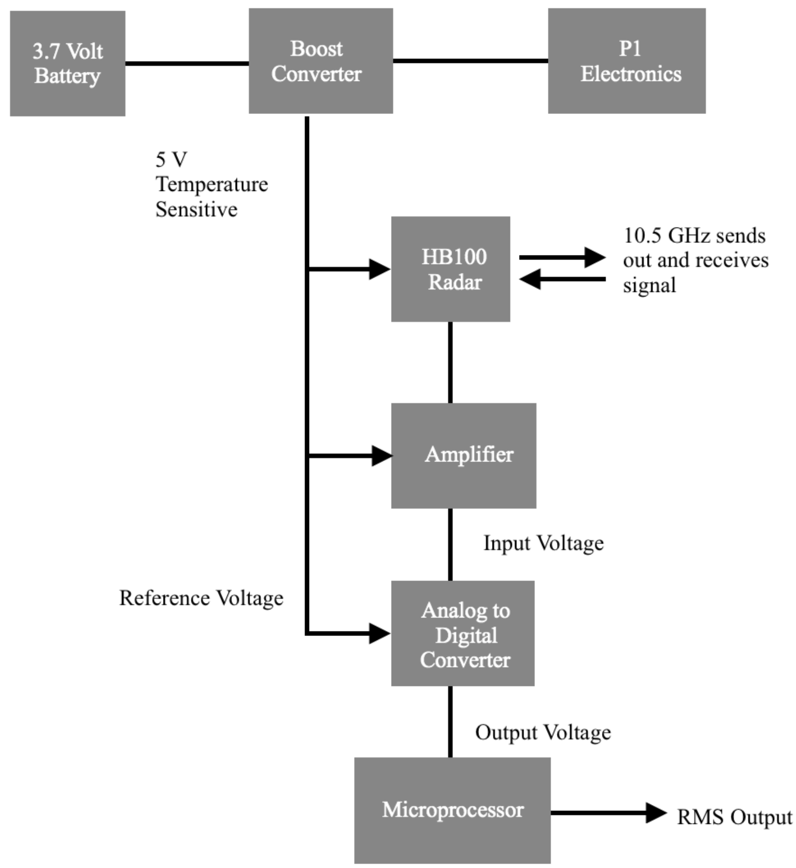


Figure A.4 Schematic of the Doppler radar device, Prototype I.

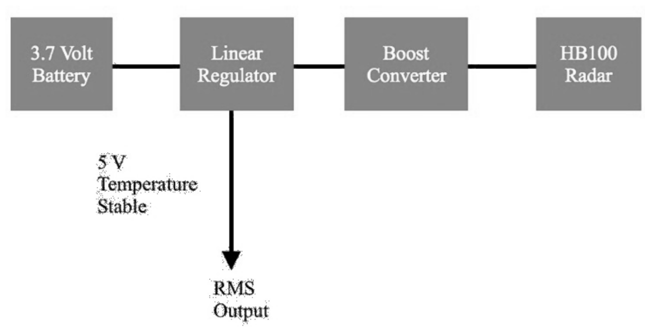


Figure A.5 Schematic of the Doppler radar device, Prototype II.

Table A.1: Model One, Demonstrating: Day, Average Internal Temperature, Internal Humidity, (External) Temperature, (External) Humidity, Solar Radiation.

	Source	**DF**	**Sums of Squares**	**F Ratio**	**Prob > F**
Overall	Model	13	8287995.5	473.4488	<0.0001
	Error	1183	1593007.7		
$r^2 = 0.837$					
Effects					
	Day	9	34536.7	2.8497	0.0025
	Bee count	1	2045025.9	1518.678	<0.0001
	Outside temperature	1	2879.6	2.1384	0.1439
	Solar radiation	1	461439.0	342.6740	<0.0001
	Humidity	1	403.8	0.299	0.5841

Table A.2. Model 2. Predicting variables which attribute to RMS across all days 7-27-17 through 8-05-17: Day, Average (External) Temperature, (External) Humidity, Solar Radiation; Excluding Internal Temperature, Internal Humidity.

	Source	**DF**	**Sums of Squares**	**F Ratio**	**Prob > F**
Overall	Model	15	619584	1246	<0.0001
	Error	1181	497		
$r^2 = 0.939$					
Effects					
	Day	9	63543.00	14.1989	<0.0001
	Bee count	1	660880.25	1329.082	<0.0001
	Average Internal Temp (F)	1	865864.64	1741.322	<0.0001
	External Temperature	1	70503.93	141.7890	<0.0001
	Solar Radiation	1	5922.35	11.9103	<0.0001
	Humidity	1	85340.15	17.1749	<0.0001
	Internal Humidity	1	24594.98	49.4624	<0.0001

Table A.3. Model 3: Predicting variables which attribute to RMS across all days 7-27-17 through 8-05-17: Day, Average (External) Temperature, Solar Radiation; Excluding Internal Temperature, Internal Humidity and (External) Humidity,

	Source	DF	Sums of Squares	F Ratio	Prob > F
Overall	Model	12	8287591.7	513.1814	<0.0001
	Error	1184	1593411.4		
$r^2 = 0.837$					
Effects					
	Day	9	34233.1	2.8264	0.0027
	Bee count	1	2044777.8	1519.392	<0.0001
	Outside temperature	1	9356.9	6.9527	0.0085
	Solar radiation	1	461321.3	342.7893	<0.0001

Table A.4 Model 4: Predicting variables which attribute to RMS across all days 7-27-17 through 8-05-17: Day, Average (External) Temperature, Solar Radiation, BeeCountxDay, External TemperaturexDay, Solar RadiationxDay; Excluding Internal Temperature, Internal Humidity and (External) Humidity,

	Source	DF	Sums of Squares	F Ratio	Prob > F
Overall	Model	39	8665589.8	211.52	<0.0001
	Error	1157	1215413.3		
$r^2 = 0.873$					
Effects					
	Day	9	83243.7	8.81	<0.0001
	Bee count	1	1103856.2	1050.80	<0.0001
	Outside temperature	1	61575.8	58.62	<0.0001
	Solar radiation	1	296458.2	282.21	<0.0001
	Bee count x Day	9	182946.7	19.35	<0.0001
	Outside temp x Day	9	68417.9	7.24	<0.0001
	Solar radiation x Day	9	146511.5	15.497	<0.0001

Table A.5. Correlation of predictive factors (correlation coefficient) based on the Fit Model Analysis procedure for RMS. Including variables of Day, Average internal temperatures, Solar Radiation Humidity, Internal Humidity, and Bee Count. Correlation of coefficients shows that temperature and humidity are strongly positively correlated r >0.70, meaning that external humidity is a redundant parameter within this model.

	Intercept	Day[07/27/2017]	Day[07/28/2017]	Day[07/29/2017]	Day[07/30/2017]	Day[07/31/2017]	Day[08/01/2017]	Day[08/02/2017]	Day[08/04/2017]	Day[08/05/2017]	Average Internal Temperature (F)	Temperature	Solar Radiation	Humidity	Internal Humidity	Bee Count
Intercept	1.0000	0.0551	-0.0917	-0.5535	-0.4815	0.1519	0.0621	0.1389	0.3055	0.3575	0.0733	-0.9134	0.1515	-0.7102	-0.0514	0.1205
Day[07/27/2017]	0.0551	1.0000	0.0584	-0.1299	-0.2307	-0.3837	-0.3507	-0.3566	-0.0901	0.1716	0.3881	0.0919	-0.0685	0.0125	-0.3946	-0.5379
Day[07/28/2017]	-0.0917	0.0584	1.0000	0.0339	-0.1489	-0.3137	-0.3185	-0.4183	-0.1925	0.1045	0.2433	0.2054	-0.1184	0.3571	-0.4494	-0.0497
Day[07/29/2017]	-0.5535	-0.1299	0.0339	1.0000	0.2068	-0.2130	-0.1799	-0.2129	-0.2417	-0.1775	0.0314	0.5428	-0.2755	0.4618	-0.1230	0.1010
Day[07/30/2017]	-0.4815	-0.2307	-0.1489	0.2068	1.0000	-0.0437	0.0072	0.0470	-0.1870	-0.3383	-0.1819	0.3803	-0.0750	0.2256	0.2393	0.0621
Day[07/31/2017]	0.1519	-0.3837	-0.3137	-0.2130	-0.0437	1.0000	0.2231	0.2946	-0.0265	-0.2970	-0.2500	-0.3210	0.1685	-0.2221	0.4853	0.1971
Day[08/01/2017]	0.0621	-0.3507	-0.3185	-0.1799	0.0072	0.2231	1.0000	0.3086	-0.0404	-0.3487	-0.2918	-0.2326	0.1761	-0.2016	0.5287	0.0975
Day[08/02/2017]	0.1389	-0.3566	-0.4183	-0.2129	0.0470	0.2946	0.3086	1.0000	0.0659	-0.3471	-0.3941	-0.3317	0.2093	-0.4536	0.6926	0.1492
Day[08/04/2017]	0.3055	-0.0901	-0.1925	-0.2417	-0.1870	-0.0265	-0.0404	0.0659	1.0000	0.0155	-0.0696	-0.2892	0.0761	-0.3132	0.0774	0.0640
Day[08/05/2017]	0.3575	0.1716	0.1045	-0.1775	-0.3383	-0.2970	-0.3487	-0.3471	0.0155	1.0000	0.2710	-0.1694	-0.0014	-0.0267	-0.5403	0.0246
Average Internal Temperature (F)	0.0733	0.3881	0.2433	0.0314	-0.1819	-0.2500	-0.2918	-0.3941	-0.0696	0.2710	1.0000	-0.0906	-0.5297	0.2307	-0.5135	-0.4216
Temperature	-0.9134	0.0919	0.2054	0.5428	0.3803	-0.3210	-0.2326	-0.3317	-0.2892	-0.1694	-0.0906	1.0000	-0.1755	0.7061	-0.2544	-0.1284
Solar Radiation	0.1515	-0.0685	-0.1184	-0.2755	-0.0750	0.1685	0.1761	0.2093	0.0761	-0.0014	-0.5297	-0.1755	1.0000	-0.0745	0.2578	-0.0220
Humidity	-0.7102	0.0125	0.3571	0.4618	0.2256	-0.2221	-0.2016	-0.4536	-0.3132	-0.0267	0.2307	0.7061	-0.0745	1.0000	-0.4403	-0.0125
Internal Humidity	-0.0514	-0.3946	-0.4494	-0.1230	0.2393	0.4853	0.5287	0.6926	0.0774	-0.5403	-0.5135	-0.2544	0.2578	-0.4403	1.0000	0.0642
Bee Count	0.1205	-0.5379	-0.0497	0.1010	0.0621	0.1971	0.0975	0.1492	0.0640	0.0246	-0.4216	-0.1284	-0.0220	-0.0125	0.0642	1.0000

Table A.6. Correlation of predictive factors (correlation coefficient) based on the Fit Model Analysis procedure for RMS. Including variables of Day, Bee Count, Temperature, and Solar Radiation. The correlation of coefficients shows that none of the weather predictors are strongly correlated for bee count, outside temperature, and solar radiation. Therefore, there are no redundancies in predicting parameters responsible for RMS.

	Intercept	Day[07/27/2017]	Day[07/28/2017]	Day[07/29/2017]	Day[07/30/2017]	Day[07/31/2017]	Day[08/01/2017]	Day[08/02/2017]	Day[08/04/2017]	Day[08/05/2017]	Bee Count	Temperature	Solar Radiation
Intercept	1.0000	-0.2492	0.0582	-0.3703	-0.3202	0.3382	0.2453	0.1047	0.1064	0.1984	0.3244	-0.9892	0.4699
Day[07/27/2017]	-0.2492	1.0000	-0.1175	-0.1144	-0.0698	-0.2533	-0.1761	-0.1689	-0.1308	-0.1353	-0.5287	0.2921	0.1912
Day[07/28/2017]	0.0582	-0.1175	1.0000	-0.1313	-0.1350	-0.1228	-0.1169	-0.1257	-0.1233	-0.1245	-0.0229	-0.0396	-0.0054
Day[07/29/2017]	-0.3703	-0.1144	-0.1313	1.0000	0.0836	-0.1935	-0.1761	-0.0880	-0.1106	-0.1587	0.1059	0.3476	-0.3776
Day[07/30/2017]	-0.3202	-0.0698	-0.1350	0.0836	1.0000	-0.1999	-0.1763	-0.0969	-0.1100	-0.1428	0.0102	0.3046	-0.2448
Day[07/31/2017]	0.3382	-0.2533	-0.1228	-0.1935	-0.1999	1.0000	-0.0447	-0.0704	-0.0810	-0.0545	0.2132	-0.3347	0.0586
Day[08/01/2017]	0.2453	-0.1761	-0.1169	-0.1761	-0.1763	-0.0447	1.0000	-0.0889	-0.0888	-0.0792	0.0692	-0.2295	0.0380
Day[08/02/2017]	0.1047	-0.1689	-0.1257	-0.0880	-0.0969	-0.0704	-0.0889	1.0000	-0.0612	-0.0397	0.1409	-0.1252	0.0297
Day[08/04/2017]	0.1064	-0.1308	-0.1233	-0.1106	-0.1100	-0.0810	-0.0888	-0.0612	1.0000	-0.0462	0.0589	-0.1167	0.0679
Day[08/05/2017]	0.1984	-0.1353	-0.1245	-0.1587	-0.1428	-0.0545	-0.0792	-0.0397	-0.0462	1.0000	0.0884	-0.2195	0.2218
Bee Count	0.3244	-0.5287	-0.0229	0.1059	0.0102	0.2132	0.0692	0.1409	0.0589	0.0884	1.0000	-0.4162	-0.3311
Temperature	-0.9892	0.2921	-0.0396	0.3476	0.3046	-0.3347	-0.2295	-0.1252	-0.1167	-0.2195	-0.4162	1.0000	-0.4688
Solar Radiation	0.4699	0.1912	-0.0054	-0.3776	-0.2448	0.0586	0.0380	0.0297	0.0679	0.2218	-0.3311	-0.4688	1.0000

AUTHOR'S BIOGRAPHY

Ana Eliza Souza Cunha is a third-year biology and pre-medical science major with minors in psychology and neuroscience, has a passion for helping people. From studying migrational patterns of wood frogs, to evaluating a radar that measures external bee activity, to studying solarization and tarping for weed management on organic vegetable farms, her undergraduate research and opportunities have been chosen by her as a way to give back to her community as well as the state of Maine as whole. Visiting most of the agricultural regions of the state of Maine Cunha has seen the more rural side of Maine and has realized the immediate need for physicians in these areas. Therefore, after graduation, Cunha plans to take a gap year before applying to medical schools. She hopes to continue working as a Certified Nursing Assistant (CNA) in order to gain more clinical hours and hopes to also eventually get her Master's Degree in public health. The next big question to tackle for her to answer is how she can help expand health care in the country.