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Federal Aviation Administration William J. Hughes Technical Center Aviation Research Division Atlantic City International Airport New Jersey 08405

# Minimizing Risk of Bird Strike to Rotorcraft 

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| 16. Abstract <br> This research presents a set of investigation emitting diodes (UVLEDs) in 'real-world' <br> The research measured the effectiveness of avoidance behavioral responses, which wo of field trials involved a one-quarter scale aircraft performing flight operations, with performance of agricultural chemical deliv Concrete examples are illustrated througho deterrence device ON/OFF condition of the environmental conditions. The environmen the bird's visual system to the approaching direction, altitude, or speed as recorded by air vehicle with a majority of plane-bird in derived variables $(\boldsymbol{V} 1, \boldsymbol{V} 2$, and $\boldsymbol{V} 3)$ of the 1 modern neurophysiological research. The incorporated in the model that differentiate speed. Multiple species of birds were invol (PAR46 size) landing light that incorporate may be uniquely associated with the specie | n results of a prototype flight conditions for the using a prototype Bird uld increase flight path remote controlled (RC) nominal flight speeds of ery. <br> out the report to make the e PAR46 with UVLED tal flight conditions we plane, corresponding to an on-board video camera teractions occurring at 3 model correspond to three SNR of the air vehicle to s the predicted distance lved in these field trials, d UVLEDs. Difference es neurophysiological fu | (PAR46 size) land e benefit of Bird Str <br> UVLEDs integrat separation to reduce plane. The second of 150 kt and $<100$ <br> he concepts clear. F landing light was ere recalculated to to the time of chang mera. The camera w 3-10m AGL with a ree sequential steps to the background b of the birds' dista , which benefited f es of reaction distan unctions. | light that incorporated ultraviolet light e Mitigation for Rotorcraft. <br> into a PAR46 landing light to trigger bird he incidence of bird strikes. The first set of field trials involved an AirTractor 802 bove ground level (AGL), in the <br> d data of measured bird responses to the istically modeled for correlation with ermine the SNR (signal to noise ratio) of in bird behavior identified as flight mounted in the cockpit of an AirTractor irspeed of 150 kt . The three empirically volved in visual processing as presented by ghtness of the sky is a key factor of change in flight direction, altitude, or the ON condition of the prototype were measured for various species, which |
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## Acronyms

| Acronym | Definition |
| :--- | :--- |
| AGL | Above ground level |
| ATC | Air traffic control |
| FAA | Federal Aviation Administration |
| LED | Light-emitting diode |
| LiPo | Lithium polymer battery |
| RC | remote controlled |
| SNR | signal-to-noise ratio |
| UVLEDs | ultraviolet light emitting diodes |
| WHA | Wildlife Hazard Assessments |
| WHMP | Wildlife Hazard Management Plan |

## Executive summary

Current methods of bird strike mitigation need to be improved to reduce both human and avian morbidity, mortality and financial losses for rotorcraft, as well as all air vehicles. After considering current mitigation techniques and their theoretical basis, and reviewing the literature of the most recent research of avian neuropathophysiology, a novel approach using ultraviolet light emitting diodes (UVLEDs) in landing lights was developed with the goal to further reduce bird strikes.

This research measured the effectiveness of using a prototype PAR46 landing light with UVLEDS (PAR46 ${ }_{\text {UVED }}$ ) to effect a bird avoidance behavioral response that would increase flight path separation thereby reducing the incidence of bird strikes. The first set of field trials involved a $1 / 4$-scale remote controlled ( $\boldsymbol{R C}$ ) plane. The second set involved an AirTractor 802 aircraft, flying at nominal speeds ( 150 kt ) and $<100^{\prime}$ above ground level $(\boldsymbol{A} \boldsymbol{G} \boldsymbol{L})$, in the performance of agricultural chemical delivery.

Field data of measurements of bird responses to the deterrence device $\boldsymbol{O N}$ vs $\boldsymbol{O F F}$ condition were statistically modeled for correlation with environmental conditions. The signal to noise ratio ( $\boldsymbol{S N R}$ ) of the bird's visual system to the approaching plane was calculated. The three sequential steps ( $\boldsymbol{V} \mathbf{1}, V \mathbf{2}$, and $\boldsymbol{V} \mathbf{3}$ ) of a visual processing model was developed based upon modern avian neurophysiological research to provide a predicted distance to the plane-bird interactions.

This study demonstrated increased flight path separation between all bird species and air vehicles with $\boldsymbol{P A R 4 6}_{\text {UVLED }}$ landing light turned $\boldsymbol{O N}$ vs $\boldsymbol{O F F}$, as measured in the field tests. The results of this 'real-world' field study measured the behavioral responses for different avian species that the avian visual perception model predicted. The results are supportive of the modern visual processing model involving three sequential steps representing visual capture, retinal neural coding response, and the brain's sensing complex nonlinear neural response. Further investigation in the underlying complexities of the Optical-Visual-Cognitive Theories offers new insights to reducing the risks of bird strikes.

The results demonstrated increased flight path separation between birds and air vehicles with PAR46 ${ }_{\text {UVLED }}$ were statistically significant. The increased bird's awareness and quicker behavioral response to the approaching air vehicle offers a reduction of the risk of a bird strike. The prototype landing light is designed to be readily installed and operated in any air vehicle without requiring modifications or adding to the pilot's workload. The operation of the PAR46 ${ }_{\text {UVED }}$ landing light is at the discretion of the pilot.

## 1 Introduction

This research was undertaken in response to DTFACT-16-R-00021, AAQ-610 Facilities \& Grants, solicitation posted by the Federal Aviation Administration William J. Hughes Technical Center. The goal of this task was to research Bird Strike Mitigation Processes for Rotorcraft.

### 1.1 Purpose

This research was structured to measure the reaction of flying birds to approaching air vehicles fitted with a fully functional PAR46 landing light that incorporated $\boldsymbol{U}$ VLEDs. The field tests were conducted in northeastern rural Arkansas where flooded rice and irrigated soybean fields are found. The test site chosen was the airfield (FAA Identifier 48AR) owned and operated by an agricultural pilot located east of Fisher, Arkansas, USA ( $35^{\circ} 29^{\prime} 17.0^{\prime \prime} \mathrm{N} 90^{\circ} 50^{\prime} 28.3^{\prime \prime} \mathrm{W}$ ) (see Figure 1).


Figure 1. Radar, airfield, and range limit of flight operations from radar unit for first field test. The birds' tracks are color coded to show flight direction.

The first field test utilized a $1 / 4$-scale remote-controlled $(\boldsymbol{R C})$ plane flown in a straight, level altitude and constant airspeed with an intersecting flight path between the aircraft and birds at approximately the same altitude. All flight operations for both field trials were conducted during daylight hours. The birds were exposed to the illumination of a single PAR46 UVLED $^{\text {P }}$ landing light mounted on a $\boldsymbol{R C}$ aircraft, which were both remotely controlled from the ground. The $\boldsymbol{R} \boldsymbol{C}$ plane
was flown in the direction of flocks of geese and ducks throughout the month of November 2018. The behavioral effect of birds interacting with an $\boldsymbol{R C}$ aircraft in flight was recorded by radar, cameras, and multiple human observers. Flight duration with the $1 / 4$-scale model airplane was limited to 15 minutes due to the capacity of onboard fuel, limiting operations to one-mile distance from the pilot's location on the airfield.

The second field test, which utilized an AirTractor 802 air vehicle, was performed within 60 km of the airfield at nominal flight speed of 150 kt and $<100^{\prime} \boldsymbol{A} \boldsymbol{G L}(77 \mathrm{~m} / \mathrm{s} @ 3-10 \mathrm{~m} \boldsymbol{A} \boldsymbol{G L}$ typical) in the performance of agricultural chemical delivery. This involved straight and level flights during delivery of chemicals as it traversed the agricultural fields during the months of January through April 2021.

### 1.2 Background

This document presents results from two separate field studies to understand 'real world' bird behavior to an approaching air vehicle configured with PAR46 ${ }_{\text {UVLED }}$ landing light(s) that were either $\boldsymbol{O N}$ or $\boldsymbol{O F F}$. The derived model was developed using widely accepted laws of optics and engineering in conjunction with the most recent postulates of avian neurophysiology.

The risk, frequency, and potential severity of wildlife-aircraft collisions are expected to grow over the next decade based on increasing air traffic, growing bird populations, and the increased use of aircraft with fewer engines. The annual cost of wildlife strikes is projected to be a minimum of $\$ 142$ million in the USA, and some estimates list it at twice this number [1]. This includes a minimum of 71,253 hours of aircraft downtime for the aviation industry [1]. Aviation bird strikes effect many stakeholders, including pilots, mechanics, airlines, airport operators, air traffic controllers, wildlife personnel, aviation safety analysts, airplane and engine manufacturers, flight training organizations, military operations, and the traveling public.

The reported incidence of aircraft bird strikes to both rotorcraft and fixed-wing aircraft is increasing despite current wildlife mitigation techniques [2]. This study explores a novel approach to reducing bird strikes and does not conform to prior aviation study models, which to date have not found an effective midair mitigation system. Bird strikes to rotorcraft and fixedwing aircraft pose a major threat, and more effective techniques are needed to mitigate these bird strikes [1]. A total of 1,758 rotorcraft bird strikes were recorded between 1990 and March 2016, of which $582(33 \%)$ damaged the rotorcraft. The species of the bird strike was identified only $37 \%$ of the time [3]. The number of bird strikes occurring during the day was $54 \%, 42 \%$ at night, and $4 \%$ during dusk/dawn hours [3]. The FAA Wildlife Database shows that $69 \%$ of the reported rotorcraft bird strikes occurred during the en route phase of flight. Rotorcraft typically cruise at
altitudes between 150 and $1,500 \mathrm{~m}$ and are exposed to a greater bird strike risk than fixed-wing aircraft that cruise at altitudes of approximately $11,000 \mathrm{~m}$ [3].

The Fact Sheet, the Federal Aviation Administration's (FAA) Wildlife Hazard Mitigation Program, reports that in the decades from 1988 to 2018, wildlife strikes have killed more than 287 people and destroyed over 263 aircraft globally [3]. Birds were involved in $95 \%$ of those strikes [1]. The number of reported strikes increased from 2000 to 2017 by $144 \%$ in the USA, while the number of damaging strikes declined $16 \%$ [1]. Bird strike reporting has increased 7.4 times from 1,850 in 1990 to over 13,000 for the last four years 2014-2017 (14,496 in 2017) [1]. The FAA mandated strike reporting for air traffic control (ATC) personnel (ATO Order JO 7210.632: January 30, 2012) and established an outreach effort to increase awareness several years ago, which contributed to a general increase in reporting. Airport management has a duty under FAR Part 139 to mitigate wildlife hazards on the airport. ATC has a duty under FAA Order 7110.65, paragraph 2-1-22, to inform other pilots, other ATC facilities, and automated flight service stations about the hazard. The gradual decrease in $5 \%$ of reported strikes as damaging strikes is attributed to the general increase in reporting of all strikes, and numerous design and ruggedness improvements by aircraft manufacturers.

Bird strikes at or near airports during takeoff or landing account for about $90 \%$ of the total number of reported bird strikes involving civil aircraft [1]. The FAA requires airport sponsors to conduct Wildlife Hazard Assessments (WHA) and prepare Wildlife Hazard Management Plans (WHMPs) to mitigate wildlife hazards through habitat modification, harassment technology, and research [4]. While most bird strikes occur on the ground or at low altitude, they also occur in flight. This group of bird strikes is outside the range of airport centric control measures.

A review of the literature demonstrates three techniques currently employed to reduce bird strikes [5], as follows:

1. Aircraft engineering to reduce the damage of collision
2. The creation of airport bubbles to keep wildlife out of vulnerable flight areas
3. Flight path separation modalities to detect and modify flight paths of aircraft or birds

A technique that enables increased flight path separation by inducing an earlier response by the birds would offer an opportunity to further reduce bird strikes both at airports and during en route flight operations. This technique would be beneficial in a variety of high-risk environments, such as low altitude and high speeds, and for flight operations in areas without the benefit of airfields using wildlife management practices [5].

Avian color research is patterned on human color models that do not account for the complexities of the neurophysiological and cognitive mechanisms involved in avian vision and object recognition [6, 7]. Several recent studies of the avian anatomy and neurophysiology responsible for visual perception contribute to a theoretical basis for mitigating bird strikes through visual sensory input $[8,9,10,11,12,13]$. The results of this 'real-world' field study is highly correlated with a new understanding of avian visual perception and behavioral response patterned upon the modern-day neurological studies, which static tetra-color chromatic contrasts models struggle to describe.

The concepts of sensory perception and cognitive recognition leading to action have been long studied. A cognitive process may involve various forms: attention, thought, learning, etc. The theoretical question on the structural mechanism of visual sensing, and the relation between visual perception and cognition theories, has remained an unresolved debate since Newton discovered in 1665 (and published in 1674 and 1704) that sunlight passing through a prism separates into multiple colors could be recombined to make the light white again. Numerous theories and models have been proposed and intensely debated, starting with 'The HelmholtzHering Debate' (see Figure 2), leading to the modern-day debate by psychologists as to the nature of visual perception. The Gibson's hypothesis (1966) bottom up theory suggests that perception involves innate mechanisms forged by evolution and that no learning is required, with each successive stage in the visual pathway carrying out ever more complex analysis [14]. Gregory's theory (1970), known as the top-down processing model, proposes that contextual information based on past experiences and stored memory patterns, is interpreted like pattern recognition (see Figure 3). The most recent avian visual research suggests sequential processing involves direct and indirect neural pathways performing complex linear, nonlinear, algebraic, and differential signal processing involving directionally sensitive neurons [8, 12, 15, 16]. A typical retinal ganglion cell presents a center region with either excitation or inhibition and a surround region with the opposite sign and bounded by the resolving power and the lateral inhibition. The retinal ganglion cell structure varies from species to species. However, the underlying biological and neurological interactions are similar.

## Neuro-science vs. Color Perception



Figure 2. Divergence of Neuro-science vs Color Perception Theories

## Cognitive Psychology Follows Perception Psychology



- Perception
- Thinking
- Memory
- Attention
- Language
- Problem-solving
- Learning...

Internal mental processes leading to behavioral response is dependent upon perception.

Figure 3. Divergence of Optical-Visual-Cognitive Theories

Birds commonly have tetrachromatic color sensitivity seeing red, green, blue, and ultraviolent spectral ranges in combination with rods, whereas humans have rods and trichromatic vision with retinal cone receptors for red, green, and blue only [9, 17]. Studies demonstrate that avian visual systems can vary within species [12, 13, 15, 16, 17, 18, 19, 20, 21]. Pulsing light is known to induce pupil dilation and improve motion perception [22]. The presence of UV wavelengths improves the temporal resolution of the avian visual system [17] and reduces Sandhill Crane collisions with power lines [22]. Recent research efforts to relate chromatic contrast theories are being extrapolated to describe behavioral responses within the predator-prey framework and studied the shape of drones as a frightening device [23]. More research needs to be done to validate these theories to increase our understanding of avian behavioral responses.

The avoidance of an imminent encounter between a bird and air vehicle requires an awareness of the risk of an impending collision for the bird(s), the aircraft, or both. Increasing the distance at which awareness of an impending convergence of flight paths occurs increases the time available to react, thereby decreasing the risk of collision. This study follows the new understanding of the complex biological mechanisms of avian vision [10, 13, 15, 16, 20, 21]. A range of avian behaviors involving self-control, working memory, and cognitive flexibility have been studied within an evolutionary framework. Comparative avian studies have identified differences in avian brain structures [20]. Species-specific electrical pathways processing visual color information have been identified. The early impulse of the birds' visual sensors triggers the transmission signal to the brain enabling an awareness and a behavioral response to that signal. The behavioral response may vary by the individual bird or within a flock's behavioral pattern. This understanding led to the development of the prototype landing light. The goal of the research was to measure the difference of plane-bird midair interactions with random flocks of varying sizes of varying avian species in their natural (wild) environment when illuminated by PAR46 ${ }_{\text {ulled }}$.

Figure 4 shows the prototype PAR46 ${ }_{\text {UVLED }}$ landing light mounted in a workbench test fixture. Note that the operation of the UVLEDs does not interfere with the white landing light function, which produces 20.78 W of emitted power per set of UVLEDs. The 420 nm LEDs were switched at a rate greater than 30 hertz ( Hz ) while the 395 nm and 375 nm LEDs are alternatively switched at a rate less than 2 Hz . The PAR46uvLED sequentially pulsed the three UVLEDs, while the white LEDs were continuously turned ON when the $\boldsymbol{P A R 4 6}_{\text {UVLED }}$ was powered. The custom fabricated electronic circuit of the landing light incorporates multiple LED drivers for four types of LEDs: white color, mono-color 420 nanometer (nm), mono-color 395 nm , and mono-color 375 nm . The near-UV wavelengths selected are well matched to the known peak sensitivity wavelengths of avian short wavelength cones [17]. A microcontroller unit independently
managed power to each of the LEDs. The white LEDs were continuously $\boldsymbol{O} \boldsymbol{N}$, while each color set of UVLEDs were alternatingly pulsed to produce a repeating pattern of flash output. Each color set of UVLEDs was powered with 22.2 VDC at 1.8 A ( 39.96 W ). The LED power conversion efficiency is $52 \%$. The measured constant luminance of the fabricated PAR46 ${ }_{\text {UVLED }}$ landing light was greater than 300 lux $(\boldsymbol{k} 1)$ at $9.1 \mathrm{~m}(\boldsymbol{k} 2)$ from the surface of the light. The measurement distance of 9.1 m was required to prevent the landing light from saturating the probe and to avoid the near-field light propagation effects of the landing light.


Figure 4. Prototype PAR46 ${ }_{\text {UVLED }}$ landing light operating in a test fixture
The PAR46uveed had a circular field of illumination of $\pm 15^{\circ}$. The 28 V direct current (VDC) with 6.2 amperes (Amps) current supplied by the lithium polymer ( LiPo ) batteries fulfilled the power requirements during flight operations with the $1 / 4$-scale model airplane. The AirTractor 802 landing light electrical circuit powered and controlled the pair of PAR46 UVLED as a constant $\boldsymbol{O N}$ or $\boldsymbol{O F F}$ light (no 'wing-wag' blinking).

The first field trial involved the use of a $1 / 4$-scale $\boldsymbol{R C}$ airplane at reduced air speeds, while the second field trial involved a full-sized air vehicle performing flight operations at nominal 150 kt air speed. Both field studies followed nominal straight and level flight profiles. The first field trial exclusively involved mid-air plane-bird interactions. The second field trial involved a mix of mid-air as well as ground-air plane-bird interactions with a flying air vehicle.

Both field trials involved the collection of field-recorded data or calculated values for each plane-bird interaction (see Table 1).

Table 1. Field recorded and calculated values (plane-bird interaction)

| DATA | How recorded |
| :--- | :--- |
| Date | Month, day, year |
| Time | GPS referenced |
| Temperature | Celsius |
| Wind speed | Meters per second |
| Wind direction | Compass points |
| Precipitation rate | Mist, moderate, heavy |
| Cloud cover | Clear, partly, overcast (Illuminance $[\boldsymbol{I}]$ <br>  <br> Lux) |
| Birds species | Geese, ducks, mixed passerines |
| Bird number | Estimated flock size |
| Bird direction | Compass points |
| Bird speed | Meters per second |
| Birds altitude | Meters |
| Direction of diversion | Left, right, reversal, Mixed |
| Reaction energy expended (Epb) | None, mild, moderate, strong |
| Plane direction | Compass points |
| Plane speed $A$ | Meters per second |
| Plane altitude | Meters |
| PAR46 with UVLEDs | ON, OFF (1, 0) |
| Plane-bird distance (Dpb) | Meters (radar, etc.) |
| Plane/bird intercept angle | Behind, side, head-on |
| Plane backlit by the sun | Behind, side, head-on |
| PAR46 irradiance @ plane bird distance <br> (Ee) | Lux (calculated) |
| Signal-to-noise ratio (SNR) | Numerical ratio |
| Plane detection of eye (PD(eye)) | Figure of merit (calculated) |

The illuminance (I) was measured by facing the probe of a HS1010 Illuminance Brightness Lux Meter/Light Meter manufactured by Bonajay (Shenzhen) Technology Co., Ltd., which is calibrated for CIE photo optic spectral response, in the opposite direction of the sun.

The three empirically derived variables ( $\boldsymbol{V} 1, \boldsymbol{V} 2$, and $\boldsymbol{V} 3$ ), representing each sequential step involved in visual processing, were calculated for each field trial with the complete $\boldsymbol{O N}$ vs $\boldsymbol{O F F}$ dataset. The three high-level variables independently encompass several different models
(chromatic contrast, optical flow, predator-prey behavior, etc.) measured physiological and behavioral differences of species in a complimentary manner without bias. The comparison of the predicted distance of plane-bird interaction distance was correlated to the actual plane-bird distance separately for the both $\boldsymbol{O N}$ and $\boldsymbol{O F F}$ datasets. Further analysis of the data subset categorizing different bird species from the second field trial is presented.

The intensity factor $(\boldsymbol{F I})$ is a premeasured constant value of the relative illuminance of different portions of the sky for each compass point compared to the referenced illuminance value (I) measured at the start of each flight operation. The brightness of the sky predictably changes between looking toward the sun or away from the sun. The $\boldsymbol{F I}$ constant values were revalidated periodically throughout the first field trial. The $\boldsymbol{F I}$ constant values were utilized for the second field trial without revalidating the values. The predetermined constant values ( $\boldsymbol{F I}$ ) were measured to represent the illuminance of the sky in the direction of the birds' flight path angle, recorded as follows:

- $1=$ sun is behind the birds
- $1.25=$ compass position $\pm 45^{\circ}$ either side
- $2.5=$ compass position $\pm 90^{\circ}$ from behind $\pm 45^{\circ}$ either side
- $6.5=$ compass position $\pm 135^{\circ}$ from behind $\pm 45^{\circ}$ either side
- $8=$ directly facing the sun $\pm 45^{\circ}$ either side.

The plane-bird distance ( $\boldsymbol{D} \boldsymbol{p} \boldsymbol{b}$ ) was measured from radar data or other field reference data to determine the flight distance of separation between birds and the plane's location. The relationship of the plane location in relation to the position of the sun from the perspective of the birds was determined using the recorded time of day and flight direction data. The sun's position was measured in $\pm 45^{\circ}$ groups from the angle of the sun to the vector direction between the plane's and birds' flight path recorded as $0=$ behind birds $\pm 45^{\circ}, 1=$ side angle $\pm 90^{\circ}$ from behind $\pm 45^{\circ}$, or $2=$ head on $\pm 45^{\circ}$.

The plane-bird intercept angle is the relationship of the plane compared to the vector paths between the plane and the birds' flight path. The resulting angle was categorized as $\pm 45^{\circ}$ by comparing the vector directions between the plane's and birds' flight path recorded as $0=$ behind birds $\pm 45^{\circ}, 1=$ side angle $\pm 90^{\circ}$ from behind $\pm 45^{\circ}$, or $2=$ head on $\pm 45^{\circ}$.

The power condition of the PAR46 $\boldsymbol{P A V L E D}^{\text {was }}$ wecorded as $0=\boldsymbol{O F F}$ and $1=\boldsymbol{O N}$.
The $\boldsymbol{E e}$ is the irradiance from the $\boldsymbol{P A R 4 6}_{\boldsymbol{U V L E D}}$ at the plane-bird distance $(\boldsymbol{D p b})$, as measured in lux (lumens $/ \mathrm{m} 2$ ); $\boldsymbol{k} 1$ and $\boldsymbol{k} 2$ are empirically measured constants, and $\boldsymbol{D} \boldsymbol{p} \boldsymbol{b}$ is determined from the radar and video images. The propagation of spatially and temporally incoherent light as a
function of [distance] ${ }^{-2}$ as it moves through a homogeneous medium is derived from the field data.

$$
E e=k 1 \times \llbracket \frac{(k 2)}{(D p b)} \rrbracket^{2}
$$

PHeye is an empirically calculated number that generates an arbitrary value of postulated horizontal cell groups of the eye involved in the detection of the plane's wingspan at distance ( $\mathbf{D p b}$ ). The calculated ratio of the known wingspan of the plane ( $\boldsymbol{k} 3$ ) is divided by the product of the plane-bird distance multiplied by $(\boldsymbol{k} 4)$. The $(\boldsymbol{k} 4)$ value is a constant value equal to the tangent $(\theta)$ value of $0.5^{\circ}$. The rationale for $\theta=0.5^{\circ}$ is an arbitrarily defined small region of the retina corresponding to the interconnected horizontal cells. Note that the tangent value of small angles (less than $1^{\circ}$ ) will change approximately in a linear fashion.

$$
\text { PHeye }=\frac{(k 3)}{(D p b)(k 4)}
$$

The calculated signal-to-noise ratio $(\boldsymbol{S N R})$ for each plane-bird interaction is a measure used in science and engineering that compares the level of a desired signal to the level of background noise. The equation for $\boldsymbol{S N R}$ is the ratio of the desired signal to the level of background signal (noise). The desired signal is the illuminance striking the bird's eye from the plane and PAR46uVLED added to the background noise. The value of the background signal is defined as the illuminance of the sky in the direction of the birds' flight path measured by the illuminance flux measured at the start of each flight operation multiplied by the intensity factor (FI). It is the measure of irradiance of the light striking the bird's eye capable of causing various reactions such as pupillary dilation and accommodation reflex actions.

$$
\begin{equation*}
S N R=\frac{((E e) x(\text { PAR46 ON or OFF }))+((I) x(F I))}{(I) x(F I)} \tag{3}
\end{equation*}
$$

Three variables ( $\boldsymbol{V} 1, \boldsymbol{V} 2$, and $\boldsymbol{V} 3$ ) are empirically derived values, which represent each sequential step involved in visual processing. The first variable ( $\boldsymbol{V} 1)$ is the value representing a bird's eye visual capture (i.e., optical system) for each plane-bird interaction equal to PHeye. The second variable ( $\boldsymbol{V} 2$ ) representing the retinal neural coding response to the bird's eye visual capture of the object by logarithmically adding the value PHeye with the signal strength defined as $\boldsymbol{S N R}$ (i.e., retinal neural processing) for each plane-bird interaction. The third variable (V3) is the value associated with the portion of the brain capable of sensing complex nonlinear neural response (i.e., changes in motion or patterns of an object) for each plane-bird interaction.

The linear regression analysis framework utilized variables $(\boldsymbol{V} 1, \boldsymbol{V} 2$, and $\boldsymbol{V} 3)$ to the predicted distance of plane-bird interaction (PDpb) for each plane-bird interaction:

$$
\begin{gathered}
V 1=(\text { PHeye }) \\
V 2=\log 10(\text { SNR })+\text { Log } 10(\text { PHeye }) \\
V 3=(V 2)(V 2)
\end{gathered}
$$

These tests were used to analyze the dataset. Two tests, the Mann-Whitney and the two-sample Kolmogorov-Smirnov test from the XLSTAT-Premium software (Addinsoft, 2019; data analysis and statistics with MS Excel, Addinsoft, NY), were used. The nonparametric analysis techniques were applied to address the low conformance to a Gaussian distribution instead of a linear statistical analysis for the first field trial dataset only. Descriptive statistics and a regression method to model the three variables in a linear regression framework was obtained from the Excel Analysis ToolPak.

### 1.2.1 First field trial - experiment design

The bird radar unit was a 200 W , dopplerized capable S band frequency radar system, with $24^{\circ}$ above ground level detection antenna configuration that performed a $360^{\circ}$ sweep every 1.6 s with a corresponding vertical radar sweep (Merlin model manufactured by DeTect Inc., Panama City, FL) (see Figure 5). The Merlin model combines independent vertical and horizontal radar data to measure altitude. The radar unit did not record flight activities that were within that horizontal sweep cone of silence (see Figure 6). The radar tracks documented the location and altitude of the birds, and the flight behaviors of the flocks following the plane-bird interaction were recorded as ( $\boldsymbol{R p b}$ ) intensity of bird response values. The camera mounted on the plane documented many avian behavioral responses not recorded by the radar. The temperature, wind direction, wind speed, and time were recorded by the airfield instrumentation (see Supplemental Material - spreadsheet) at the start of each flight operation.

The $1 / 4$ scale $\boldsymbol{R C}$ plane was a Valiant Model Hangar 9 design (Horizon Hobby LLC, Champaign, IL) with a color scheme consisting of a white background and red stripes. It has a 2.8 m wingspan with approximately 1.07 m 2 wing surface area. The engine was a DLE 56RA gas engine with a tuned muffler system. The sound produced by this plane at full throttle was less than 96 dB at a distance of 6.1 m . A uniformly high throttle setting was utilized for all plane-bird interactions. All hardware and flight operations conformed to the Academy of Model

Aeronautics flight requirements. The additional payload consisted of the PAR46 ${ }_{\text {UVLED }}$, a highdefinition camera ( $110^{\circ}$ field of view, $1920 \times 1080$ pixels, and 30 fps ), lithium polymer (LiPo) batteries, controlling electronics, and relays to enable the ON/OFF operation. The PAR46 ${ }_{\text {UVLED }}$ was mounted in the location where the cockpit windscreen would be located. The total weight of the additional payload was approximately 5 kg depending upon the capacity size of LiPo batteries used. Flight speed was generally limited to less than 21 m per second.


Figure 5. Bird detection radar location adjacent to the airstrip and hangar


Figure 6. Radar cone of silence as viewed from the cockpit
We found that the radar results were difficult to interpret when the field was overwhelmed with thousands of birds or multiple flocks traveling in dense groups in multiple directions. Some plane-bird interactions could not be corroborated with multiple record sets. Some of the flock reactions occurred beyond the view of the plane's camera, but they were seen by multiple human observers. Any bias in the collection or interpretation of the radar data is assumed to be equally applied to all data points collected.

### 1.2.2 Second field trial - experiment design

A single forward-facing GoPro 7 Black (1080p, 30 fps ) camera mounted in the cockpit of the AirTractor 802 recorded the reactions of the birds. Interaction of birds that were within the direct
flight path of the air vehicle were recorded by the camera, which was configured with a field of view of approximately $\pm 30^{\circ}$. The birds were exposed to the illumination from two PAR46 ${ }_{\text {UVLED }}$, which were either $\boldsymbol{O N}$ or $\boldsymbol{O F F}$ condition throughout the entire flight operation. The maximum resolution of a single camera pixel corresponds to 0.26 m at a distance of 1000 m . Any bias in the collection or interpretation of the video is assumed to be equally applied to all data points collected. The temperature, wind direction, wind speed, and time were recorded by the airfield instrumentation (see Supplemental Material - spreadsheet) at the start of each flight operation.

### 1.2.3 First field trial - subjects

Large flocks of migrating snow geese (Anser caerulescens) and year-round resident greater white-fronted geese (Anser albifrons) were the dominant species in this study. Smaller groups of migrating Canada geese (Branta canadensis) and Ross's geese (Anser rossii) were present. Homogeneous flocks of migrating snow and Canada geese would overfly the aircraft at high altitudes, greater than 100 m . Flocks of mixed species found in the surrounding fields moved from one field to another to feed or to remote fields and nearby wildlife refuges. The number of dabbling ducks dramatically decreased in the nearby feeding fields when large flocks of geese were present. Therefore, they represented a smaller portion of the plane-bird interactions. These duck species included mallard (Anas platyrhynchos), northern pintail (Anas acuta), gadwall (Mareca strepera), blue-winged teal (Spatula discors), green-winged teal (Anas carolinensis), American wigeon (Mareca americana), and northern shoveler (Spatula clypeata). The study of the visual physiology of the Canada goose (Branta canadensis) has shown that they are capable of seeing objects between $324^{\circ}$ and $340^{\circ}$ horizontal field of view, have color streaks, and have UV cone peak sensitivity measured at 411 nm with a range exceeding 380-440 nm . It is hypothesized that the species involved in this study have similar physiology [9]. Large resident and migrating populations of geese and ducks were present. Often thousands of birds were flying in our immediate area of the airport with moments when tens of thousands of birds were flying at once (see Figure 7 and Figure 8).


Figure 7. The $1 / 4$-scale $\boldsymbol{R} \boldsymbol{C}$ plane flown from the grass area adjacent to the airstrip


Figure 8. $\boldsymbol{R C}$ plane flown in the direction of large flocks of birds

### 1.2.4 Second field trial - subjects

The bird population of the second field test consisted of various resident populations, which were organized into general subsets: (Anatidae) geese \& ducks, (Icteridae) $+($ Quiscalus) blackbirds \& grackles, $($ Ardeidae $)+($ Threskiornithidae $)$ Herons \& Ibis, (Accipitridae) hawks \& eagles, (Corvidae) crows \& ravens, (Charadriinae) plover (Passerine) small body, and (Cathartidae) vulture species groups respectively. All unidentified species were categorized as an Unknown species group. The birds encountered were usually foraging in the fields or traversing between fields when the flight path of plane intersected with them.

### 1.2.5 First field trial - test and analysis procedure

Bird flight activity was the highest for several hours following sunrise or preceding sunset. The movement of cold weather fronts with predominately north winds brought large populations of migrating birds into our field of operation. We launched the $\boldsymbol{R C}$ plane for either high altitude migratory flocks at an altitude above 100 m as they were descending or local birds at lower altitude as they overflew our airspace. We interacted only with birds flying overhead and not
with birds located on the ground. All launches were from the airfield within 150 m of the radar unit located at the north end of the runway. The $\boldsymbol{R C}$ plane was operated in a manner to match the altitude of the birds and an intersecting approach flight path. The light was either continuously $\boldsymbol{O N}$ or $\boldsymbol{O F F}$ during each plane-bird interaction, which typically lasted less than 15 seconds and rarely more than 30 seconds. It was necessary to alter the plane's direction after a plane-bird interaction due to concerns of maintaining line-of-sight control and to ensure that the radio control limits were not exceeded. No predators were observed in the area during the conduct of the study.

Field data that corresponded to each plane-bird interaction were recorded. The radar measured both plane and bird speed and altitude. If either the birds or plane were not measured by the radar unit, video recording from the plane and the two additional cameras on the ground, combined with field notes, was used to estimate these values. All plane-bird interactions were traced to the global positioning system (GPS) time logged by the radar system.

### 1.2.6 Second field trial - test and analysis procedure

The unique avian family species involved in each bird-plane interaction (body size, shape, wingbeat pattern and/or flock pattern) was identified using the recorded images from the video camera. Most of the plane-bird interactions species were not identified and were assigned to an unknown group of species. The distance between the air vehicle and the bird was determined by multiplying the time difference recorded by camera between the moment of bird reaction to the approaching air vehicle and when it passed out of the field of view of the camera by the air speed of the air vehicle. The AirTractor's known $\boldsymbol{V}_{\mathbf{1}}, \boldsymbol{V}_{\mathbf{r}}, \boldsymbol{V}_{\mathbf{2}}, \boldsymbol{V}_{\mathbf{n}}$, and $\boldsymbol{V}_{\mathbf{s} 1}$ speeds corresponding to the flight condition at the time of bird-plane interactions were logged and utilized in calculating the airspace separation (distance) between the plane and the bird at the moment of reaction. The statistical treatment of the second field trial dataset follows the first field trial dataset.

### 1.2.7 First field trial - results

The mean distance of reaction of the $\boldsymbol{P A R 4 6}_{\text {UVLED }}$ landing light ON was $334.7 \mathrm{~m}(n=43)$ and OFF was $96.5 \mathrm{~m}(n=32)$. The values for the UVLED $\boldsymbol{O} \boldsymbol{N}$ ranged from 9.1 to 874.8 meters compared to values for the UVLED OFF recorded ranged from 9.1 to 676.7 m (see Table 2). The mean distance of reaction value for the lights ON is 3.5 times greater than the OFF value. The two-sample Kolmogorov-Smirnov test/two-tailed test determined that the distributions of the two datasets differ significantly (see Figure 9 and Figure 10) and are not equal ( $D=0.674$; $p$ value (two tailed), $p<0.0001$ ). The instantaneous reaction of the birds, as recorded by either the plane's camera or from the two ground-based cameras, was noted.

Table 2. Descriptive statistics of the distance of response (meters) plane/birds $\left(D_{p b}\right)$

| Value | PAR46 UVLED <br> OFF | PAR46 UVLED <br> ON |
| :--- | :---: | :---: |
| Mean (meter) | 96.46875 | 334.7121 |
| Standard Error | 22.50258 | 31.71274 |
| Median | 61 | 292.6 |
| Mode | 15.2 | 91.4 |
| Standard deviation | 127.2938 | 207.9544 |
| Sample Variance | 16203.71 | 43245.02 |
| Kurtosis | 3.565886 | 0.285569 |
| Skewness | 676.7 | 0.837063 |
| Range | 9.1 | 874.82 |
| Minimum | 685.8 | 9.1 |
| Maximum | 3087 | 14392.62 |
| Sum | 32 | 43 |
| Count | 61.74801 | 85.56307 |
| Confidence level $(99.0 \%)$ |  |  |



Figure 9. Scattergram illustrating birds' reaction distance to plane with PAR46 $\boldsymbol{P V V E D}^{\text {P }}$ for $\boldsymbol{O N}$ vs OFF


Figure 10. Cumulative population distribution with $\boldsymbol{P A R 4 6}_{\text {UVLED }}$ ON vs $\boldsymbol{O F F}$

### 1.2.8 Second field trial - results

The mean distance of reaction of the $\boldsymbol{P A R 4 6}_{\text {UVLED }}$ landing light ON was $152.67 \mathrm{~m}(n=170)$ and $\boldsymbol{O F F}$ was $99.83 \mathrm{~m}(n=59)$. The values for $\boldsymbol{O N}$ ranged from 17 to 1334 meters. The values for the $\boldsymbol{O F F}$ recorded ranged from 25.5 to 296 m (see Table 3). The mean distance of reaction value for the lights $\boldsymbol{O N}$ is 1.5 times greater than the $\boldsymbol{O F F}$ value.

Table 3. Descriptive statistics of the distance of response (meters) plane/birds $\left(D_{p b}\right)$

| Value | PAR46uvLED <br> $\boldsymbol{O N}$ | PAR46 UVLED <br> $\boldsymbol{O F F}$ |
| :--- | :---: | :---: |
| Mean (meter) | 152.6700588 | 99.8338983 |
| Standard Error | 11.411 | 7.988 |
| Median | 119.8 | 78.3 |
| Standard deviation | 127.2938 | 207.9544 |
| Sample Variance | 16203.71 | 43245.02 |
| Range | 1317.000 | 270.500 |
| Minimum | 1334.000 | 25.500 |
| Maximum | 170 | 296.000 |
| Sum | 175.197 | 5890.200 |
| Count | 175.197 | 115.824 |
| Upper bound on mean (95\%) | 115.824 |  |
| Upper bound on mean (95\%) |  |  |

The Two-sample t-test and z-test determined that the distributions of the two datasets is significantly different (see Figure 11) and are not equal ( $p$-value (two tailed), $p<0.0001$ ).


Figure 11. Scattergram of birds' reaction distance to plane with $\boldsymbol{P A R 4 6}_{\text {UVLED }} \boldsymbol{O N}$ vs $\boldsymbol{O F F}$
The plot of cumulative distribution illustrates the total difference for the birds' reaction distance to the plane with PAR46uvLED for the $\boldsymbol{O N}$ vs $\boldsymbol{O F F}$ conditions for plover (Charadriinae), herons (Ardeidae), Ibis (Threskiornithidae), hawks (Accipitridae), eagles (large birds of prey of the family (Accipitridae), vultures (Cathartidae), blackbirds (Icteridae), and grackles (Quiscalus), with a limited number of unidentified small-body (Passerine), waterfowl (Anatidae) species interactions. All unidentified species events were identified as an unknown group. Figure 12 shows the distribution for the birds' reaction distance to the plane with PAR46 ${ }_{\text {UVLED }}$ for the $\boldsymbol{O N}$ vs $\boldsymbol{O F F}$ conditions for data subset of birds above or below 10 meters $\boldsymbol{A} \boldsymbol{G} \boldsymbol{L}$, and are similar while the combined data are different. Figure 13 shows the distribution of the birds' reaction distance to the plane, with PAR46UVLED for the $\boldsymbol{O N}$ vs $\boldsymbol{O F F}$ conditions, for different species indicating differences species behavioral responses.


Figure 12. The cumulative distribution are similar for reaction distance to plane with $\boldsymbol{P A R 4 6}_{\text {UVLED }}$ for the $\boldsymbol{O N}$ vs $\boldsymbol{O F F}$ : greater than or less than 10meters $\boldsymbol{A G L}$


Figure 13. The cumulative distribution of species subsets for the birds' reaction distance to the plane with PAR46 ${ }_{\text {uVLED }}$ either $\boldsymbol{O N}$ or $\boldsymbol{O F F}$

The descriptive statistics of different species in Table 4 identifies that the $\boldsymbol{D p b}$ (distance at the moment of plane-bird reaction) varies greatly between species.

Table 4. Descriptive statistics of species distance of response $\left(D_{p b}\right)$ (meters)

| Species | PAR46 ${ }_{\text {uvLED }}$ <br> ON (mean, n) | PAR46 <br> OFF (mean, n) |
| :--- | :---: | :---: |
| (Anatidae) geese \& ducks | $(214,18)$ | $(112,8)$ |
| (Passerine) small body | $(75,5)$ | $(-, 0)$ |
| (Icteridae) (Quiscalus) <br> blackbirds \& grackles | $(212,22)$ | $(153,9)$ |
| (Ardeidae) (Threskiornithidae) <br> Herons \& Ibis | $(185,7)$ | $(72,3)$ |
| (Accipitridae) hawks \& eagles | $(119,19)$ | $(84,7)$ |
| (Corvidae) crows \& ravens | $(189,9)$ | $(109,6)$ |
| (Charadriinae) plover | $(123,14)$ | $(60,3)$ |
| unknown | $(119,73)$ | $(85,23)$ |
| (Cathartidae) vulture | $(182,1)$ | $(-, 0)$ |

### 1.2.9 First field trial - predictive distance model - ON versus $\boldsymbol{O F F}$

A multivariable linear regression model used a linear regression framework to predict the distance of reaction ( $\boldsymbol{P D P b}$ ) as the dependent variable with only field recorded data as the independent variables resulted in a low significance of correlation ( $R 2=0.146$ ). Flock size, weather conditions, temperature, wind direction, wind speed, time, date, cloud cover, precipitation, and illuminance measurements weakly correlated as independent variables. The linear regression analysis of each of the three independent variables $(\boldsymbol{V} 1, \boldsymbol{V} 2$, and $\boldsymbol{V} 3)$ are strongly correlated to $\boldsymbol{D p b}(-0.5236,-0.8674,-0.7236, n=75)$ (see Table 5). This led to the determination of three variables $(\boldsymbol{V} 1, \boldsymbol{V} 2$, and $\boldsymbol{V} 3)$ to examine the sequential regions involved in the avian visual processing system.

Table 5. Correlation of modeled variables - all empiracally derived data

|  | $\boldsymbol{E e}$ | $\boldsymbol{S N R}$ | $\boldsymbol{O N} / \boldsymbol{O F F}$ | $\boldsymbol{V}_{\boldsymbol{1}}$ | $\boldsymbol{V}_{2}$ | $\boldsymbol{V}_{\mathbf{3}}$ | $\boldsymbol{D}_{\boldsymbol{p} b}$ |
| :--- | :--- | :--- | :--- | :---: | :---: | :---: | :---: |
| $\boldsymbol{E} \boldsymbol{e}$ | 1 |  |  |  |  |  |  |
| $\boldsymbol{S N R}$ | 0.99858 | 1 |  |  |  |  |  |
| $\boldsymbol{O N} / \boldsymbol{O F F}$ | 0.11085 | 0.12824 | 1 |  |  |  |  |
| $\boldsymbol{V}_{\mathbf{1}}$ | 0.50046 | 0.49294 | -0.41562 | 1 |  |  |  |
| $\boldsymbol{V}_{\mathbf{2}}$ | 0.30602 | 0.30108 | -0.63134 | 0.84178 | 1 |  |  |
| $\boldsymbol{V}_{\mathbf{3}}$ | 0.40728 | 0.40005 | -0.57364 | 0.94349 | 0.96762 | 1 |  |
| $\boldsymbol{D}_{\boldsymbol{p}}$ | -0.12806 | -0.12981 | 0.55671 | -0.52358 | -0.86743 | -0.72355 | 1 |

The three independent variables $(\boldsymbol{V} 1, \boldsymbol{V} \mathbf{2}$, and $\boldsymbol{V} \mathbf{3}$ ) used to derive the coefficients, and intercept values (PDpb) for the predicted rate of change of Equation 7 were significant probabilities ( $p$ values for Intercept, $\boldsymbol{V} 1, \boldsymbol{V} 2$, and $\boldsymbol{V} 3$ are $5.969 \mathrm{E}-66,2.043 \mathrm{E}-19,1.219 \mathrm{E}-48$, and $6.577 \mathrm{E}-35$, respectively) (see Table 6). The resulting equation to the predicted distance of plane-bird interaction (PDpb) value is described as:

$$
\begin{equation*}
P D p b=1041+(-7)(V 1)+(-1541)(V 2)+(683)(V 3) \tag{7}
\end{equation*}
$$

Table 6. Coefficients of modeled variables for distance of plane bird interaction $\left(\mathrm{PD}_{p b}\right)$

|  | Coefficients | Standard Error | $\boldsymbol{T}$ stat | $\boldsymbol{P}$-value | Lower 95\% | Upper 95\% |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Intercept | 1041.32999 | 15.527593 | 67.06319 | $5.969 \mathrm{E}-66$ | 1010.3688 | 1072.2911 |
| $\boldsymbol{V} 1$ | -6.981792 | 0.5636363 | -12.38705 | $2.043 \mathrm{E}-19$ | -8.105651 | -5.857933 |
| $\boldsymbol{V} 2$ | -1541.101 | 40.952002 | -37.63188 | $1.219 \mathrm{E}-48$ | -1622.757 | -1459.445 |
| $\boldsymbol{V} 3$ | 683.08214 | 29.397344 | 23.236185 | $6.577 \mathrm{E}-35$ | 624.4655 | 741.69878 |

The linear regression of these three variables were strongly significant in predicting the distance of reaction to the approaching plane for either condition of the lights $\boldsymbol{O N}$ or $\boldsymbol{O F F}$. The $\boldsymbol{V} 2$ and $V 3$ variables are the more dominant with greater significance of correlation of the three variables ( $\boldsymbol{V} 1, \boldsymbol{V} 2$, and $\boldsymbol{V} 3$ ). PHeye (or $\boldsymbol{V} 1$ ) is the postulated number of horizontal cell groups of the eye involved in the detection of the plane's wingspan at distance ( $\mathbf{D p b}$ ) (i.e., analogous to image formation on a detector's surface). The $\boldsymbol{F I}$ brightness of the background sky from the perspective of the bird is the dominant variable in calculating $\boldsymbol{S N R}$. Note that the $\boldsymbol{F I}$ value applied to the $\boldsymbol{I}$ value significantly differentiates the 75 dataset $\boldsymbol{S N R}$ values, which is carried forward by the $\boldsymbol{V} 2$ and $\boldsymbol{V} 3$ values. $\boldsymbol{V} 2$ is the logarithmic addition of PHeye with $\boldsymbol{S N R}$ involving retinal image signal processing (i.e., analogous to kernel or convolution matrix amplification). $V 3$ is the result of multiplying $\boldsymbol{V} 2$ by $\boldsymbol{V} 2$, involving complex signal processing of the brain, optical nerves, and retinal neurons (i.e., analogous to the Euclidean vector that has a geometric object with magnitude and direction values).

The combined ON/OFF dataset of the three independent variables ( $\boldsymbol{V} 1, \boldsymbol{V} 2$, and $\boldsymbol{V} 3$ ) were significantly correlated to $\boldsymbol{P D p b}(R 2=0.9941, n=75)$. The interaction distance for each group of $\boldsymbol{O N} / \boldsymbol{O F F}$ were significant, correlated to $\boldsymbol{P D p b}(R 2=0.9877,0.9733, n=43,32)$ (see Figure 14).


Figure 14. Predicted distance of bird reaction - PAR46 ${ }_{\text {UVLED }}$ turned either ON or OFF

### 1.2.10 Second field trial - predictive distance model - ON versus $\boldsymbol{O F F}$

A multivariable linear regression model analysis, described in section 1.2.9, using a linear regression framework to predict the distance of reaction ( $\boldsymbol{P D} \boldsymbol{p} \boldsymbol{b}$ ) as the dependent variable, resulted in the three independent variables ( $\boldsymbol{V} 1, \boldsymbol{V} 2$, and $\boldsymbol{V} 3$ ) strongly correlated to $\boldsymbol{D p b}(-0.528$, $-0.806,-0.691, n=228$ ) (see Table 7). Flock size, weather conditions, temperature, wind direction, wind speed, time, date, cloud cover, precipitation, and illuminance measurements weakly correlated as independent variables and not utilized in this predictive model.

Table 7. Correlation of all empirally derived variables (from all data)

|  | $\boldsymbol{E} \boldsymbol{e}$ | $\boldsymbol{S N R}$ | ON/OFF | $\boldsymbol{V}_{\mathbf{1}}$ | $\boldsymbol{V}_{2}$ | $\boldsymbol{V}_{\mathbf{3}}$ | $\mathbf{D}_{p b}$ |
| :--- | ---: | ---: | ---: | ---: | ---: | ---: | ---: |
| $\boldsymbol{E} \boldsymbol{e}$ | $\mathbf{1}$ |  |  |  |  |  |  |
| $\boldsymbol{S N R}$ | 0.637 | $\mathbf{1}$ |  |  |  |  |  |
| $\boldsymbol{O N} / \boldsymbol{O F F}$ | 0.223 | 0.258 | $\mathbf{1}$ |  |  |  |  |
| $\boldsymbol{V}_{\boldsymbol{I}}$ | 0.763 | 0.536 | -0.136 | $\mathbf{1}$ |  |  |  |
| $\boldsymbol{V}_{2}$ | 0.521 | 0.440 | -0.199 | 0.889 | $\mathbf{1}$ |  |  |
| $\boldsymbol{V}_{\mathbf{3}}$ | 0.604 | 0.485 | -0.186 | 0.952 | 0.982 | $\mathbf{1}$ |  |
| $\boldsymbol{D}_{\boldsymbol{p} \boldsymbol{b}}$ | -0.240 | -0.236 | 0.171 | -0.528 | -0.806 | -0.691 | $\mathbf{1}$ |

The three independent variables ( $\boldsymbol{V} 1, \boldsymbol{V} \mathbf{2}$, and $\boldsymbol{V} 3$ ) used to derive the coefficients, and intercept values (PDpb) for the predicted rate of change of Equation 8 were significant probabilities ( $p$ values for Intercept, $\boldsymbol{V} 1, \boldsymbol{V} 2$, and $\boldsymbol{V} \mathbf{3}$ are all $<0.0001$, respectively) (see Table 8).

Table 8. Predicted distance of plane bird interaction (PDpb) - significant model parameters

|  | Coefficients | Standard <br> Error | T Stat | P-value | Lower 90\% | Upper 90\% |
| :--- | ---: | ---: | ---: | ---: | ---: | ---: |
| Intercept | 1628.349 | 16.904 | 96.329 | $<0.0001$ | 1600.429 | 1656.269 |
| $\boldsymbol{V}_{\boldsymbol{1}}$ | -8.217 | 0.319 | -25.726 | $<0.0001$ | -8.744 | -7.689 |
| $\boldsymbol{V}_{\mathbf{2}}$ | -2269.781 | 32.866 | -69.062 | $<0.0001$ | -2324.06486 | -2215.49636 |
| $\boldsymbol{V}_{\mathbf{3}}$ | 934.217 | 18.988 | 49.201 | $<0.0001$ | 902.855 | 965.579 |

The resulting equation to the predicted distance of plane-bird interaction (PDpb) value is described as:

$$
P D p b=1628+(-8.2)(V 1)+(-2269.8)(V 2)+(934.2)(V 3)
$$

The entire $\boldsymbol{O N} / \boldsymbol{O F F}$ dataset of the three independent variables ( $\boldsymbol{V} 1, \boldsymbol{V} 2$, and $\boldsymbol{V} 3$ ) were significantly correlated to $\boldsymbol{P D P b}\left(R^{2}=0.985, n=228\right)$. The interaction distance for each group of ON/OFF were significant correlated to $\boldsymbol{P D p b}\left(R^{2}=0.9847,0.9734, n=170,60\right)$ (see Figure 15).


Correlation of modeled variables for $\boldsymbol{D p b}$ and $\boldsymbol{P D} \boldsymbol{p} \boldsymbol{b}$ for plane-bird distance were organized into species data subsets (see Table 9). All subsets species $\boldsymbol{D} \boldsymbol{p} \boldsymbol{b}$ and $\boldsymbol{P} \boldsymbol{D} \boldsymbol{p} \boldsymbol{b}$ data points were highly correlated within their species group: $\left(R^{2}=0.9966,0.9966,0.9852,0.9688,0.9979,0.9858, n=\right.$ $26,31,10,26,15$, and 17 for geese \& ducks (Anatidae), blackbirds \& grackles (Icteridae) + (Quiscalus), Herons \& Ibis (Ardeidae) + (Threskiornithidae), hawks \& eagles (Accipitridae),
crows \& ravens (Corvidae), plover (Charadriinae) species groups, respectively). The small body (Passerine), vulture (Cathartidae), and unknown subsets had small sample numbers or unknown species and were not analyzed (see Figure 16).


Figure 16. Predicted distance of bird reaction of $\boldsymbol{P A R 4 6}_{\text {UVLED }} \boldsymbol{O N}$ or $\boldsymbol{O F F}$ for each species data subset

Table 9. Descriptive statistics by species distance of response ( $D_{p b}$ ) (meters)

| Species | Linear equation | $\mathbf{R}^{2}$ value |
| :--- | :---: | :---: |
| (Anatidae) geese \& ducks | $\mathrm{y}=0.9302 \mathrm{x}+9.5901$ | 0.9966 |
| (Passerine) small body | - | - |
| (Icteridae) $+($ Quiscalus $)$ <br> blackbirds \& grackles | $\mathrm{y}=1.1585 \mathrm{x}-25.388$ | 0.9966 |
| (Ardeidae) ( Threskiornithidae) <br> Herons \& Ibis | $\mathrm{y}=1.0607 \mathrm{x}-10.092$ | 0.9852 |
| (Accipitridae) hawks \& eagles | $\mathrm{y}=0.934 \mathrm{x}+8.1463$ | 0.9688 |
| (Corvidae) crows \& ravens | $\mathrm{y}=1.1673 \mathrm{x}-28.572$ | 0.9979 |
| (Charadriinae) plover | $\mathrm{y}=1.0999 \mathrm{x}-9.2488$ | 0.9858 |
| unknown | - | - |
| (Cathartidae) vulture | - | - |

## 2 Comments and recommendations

The operation concept enables the PAR46 ${ }_{\text {UVLED }}$ landing lights to be operated at the pilot's discretion. The device does not require active control by the pilot to increase flight path separation thereby enabling a reduced risk of bird strikes. The pilot remains responsible to operate the landing lights in compliance with all regulations and operational procedures requirements.

- The pilots' situational awareness to a flight operation in an environment that presents opportunities for bird encounters should lead to the powering the PAR46UVLED.
- The pilots' situational awareness to an increased risk of a bird encounter should increase the pilots' attention to the airspace surrounding the rotorcraft and preparedness for avoidance maneuvers.

The model was designed by analyzing current literature on avian neurophysiology to develop an effective method of increasing flight path separation between birds and air vehicles. The data collected throughout this study was conducted during daylight. The empirically derived model predicts the effectiveness of the device to increase the $\boldsymbol{P D} \boldsymbol{p} \boldsymbol{b}$ during nighttime vs. daytime operations due to the increased $\boldsymbol{S N R}$ (signal-to-noise ratio) of the landing light. It is noted that the $\boldsymbol{S N R}$ value is poorly correlated to predicted distance by itself.

The author recommends further study to evaluate the effectiveness of the PAR46 $\boldsymbol{P V V L E D}^{\text {to }}$ varying flight conditions and species, as follows:

- Nighttime conditions
- Varying climate and weather conditions
- Varying species flying at higher altitudes
- Wider range of bird species


### 2.1 System overview

This study demonstrated increased flight path separation between bird and air vehicles with $\boldsymbol{P A R 4 6}_{\text {UVLED }}$ landing light turned $\boldsymbol{O N}$ vs $\boldsymbol{O F F}$. The goal of increased flight path separation is to reduce bird strikes resulting from the bird's increased awareness and quicker behavioral responses to the approaching air vehicle.

The device utilized in these field trials involved a prototype landing light with three colors of UVLEDs, which were independently pulsed while operating as a white light PAR46 landing light. The prototype landing light is designed to be readily installed and operated in any air vehicle without requiring special modifications or adding to the pilot's workload. The first set of
field trials involved a $1 / 4$-scale remote controlled $\boldsymbol{R C}$ plane while the second set of field trials involved an AirTractor 802 aircraft performing flight operations at nominal flight speeds of 150 kt and $<100^{\prime} \boldsymbol{A} \boldsymbol{G L}$ in the performance of agricultural chemical delivery. The ultraviolet light emitting diodes (UVLEDs) do not impede the function of the landing light or interfere with the operation or safety of the air vehicle.

A statistically significant increase in $\boldsymbol{D} \boldsymbol{p} \boldsymbol{b}$ was measured in both field trials when the PAR46 ${ }_{\text {UVLED }}$ was powered. The variables measuring the device and the environment (temp, clouds, species, flock structure, etc.) were studied. An empirically derived model consistent with modern neurophysiological research involved three empirically derived variables ( $\boldsymbol{V} \mathbf{1}, \boldsymbol{V} \mathbf{2}$, and $V 3$ ) corresponding to three sequential steps; sensory perception, cognitive recognition, and reaction was highly correlated with $\boldsymbol{P D} \boldsymbol{p} \boldsymbol{b}$. The airspeed of the air vehicle and other environmental values were poorly correlated to $\boldsymbol{P D} \boldsymbol{p b}$. The bird location (on the ground, altitudes $<10 \mathrm{~m} \boldsymbol{A} \boldsymbol{G} \boldsymbol{L}$, or altitudes $>10 \mathrm{~m} \boldsymbol{A} \boldsymbol{G} \boldsymbol{L}$ ) with the $\boldsymbol{D} \boldsymbol{p} \boldsymbol{b}$ was poorly correlated. Flock size was poorly correlated to PDpb.

The linear regression of these three variables were strongly significant in predicting the distance of reaction to the approaching plane for either condition of the lights $\boldsymbol{O N}$ or $\boldsymbol{O F F}$. The $\boldsymbol{V} 2$ and $V 3$ variables are the more dominant variables, with a greater significance of correlation of the three variables ( $\boldsymbol{V} 1, \boldsymbol{V} 2$, and $\boldsymbol{V} 3$ ). PHeye or $\boldsymbol{V} 1$ is the postulated number of horizontal cell groups of the eye involved in the detection of the plane's wingspan at distance ( $\boldsymbol{D} \boldsymbol{p b}$ ) (i.e., analogous to image formation on a detector's surface). The $\boldsymbol{F I}$ brightness of the background sky from the perspective of the bird is the dominant variable in calculating $\boldsymbol{S N R}$. Note that the $\boldsymbol{F I}$ value applied to the $\boldsymbol{I}$ value significantly differentiates the dataset SNR values, which are carried forward by the $\boldsymbol{V} 2$ and $\boldsymbol{V} 3$ values. $\boldsymbol{V} 2$ is the logarithmic addition of PHeye with $\boldsymbol{S N R}$, and corresponds to retinal image signal processing (i.e., analogous to kernel or convolution matrix amplification). $\boldsymbol{V} 3$ is the result of multiplying $\boldsymbol{V} 2$ by $\boldsymbol{V} 2$, and corresponds to complex signal processing of the brain, optical nerves, and retinal neurons (i.e., analogous to the Euclidean vector that has a geometric object with magnitude and direction values). These field trials results and the model's validation of modern neuroscience studies add great insight to the neurophysiological process. While the optical, engineering principles, and lateral inhibition of neurons are widely acknowledged, the cognitive behavioral response is less well understood.

Species data subset analysis identified variation between mean distances recorded by $\boldsymbol{D p} \boldsymbol{b}$ and illustrated by the plot of cumulative distribution to the $\boldsymbol{P A R 4 6}_{\text {UVLED }}$, indicating significant species differences, which is well correlated to the PDpb of the three variable model for all
species measured. It is postulated the differences are related to physiological and behavioral differences of species.

The dominance of geese \& ducks (Anatidae) measured in Field Test \#1 is attributed to the comparative difference with the mean $\boldsymbol{D} \boldsymbol{p} \boldsymbol{b}$ values of Field Test \#2, which involved a diverse range and number of species.

An under sampling of some species, especially species with small body sizes, is postulated to be the result of the resolution limitations of the camera system. Plots of cumulative distribution of species data subsets supported with the mean value offsets for similar body sized birds (e.g. crows \& ravens (Corvidae) vs. plover (Charadriinae), etc.) demonstrates species differences. The diversion behavior observed consisted of changing flight direction or flight behavior to the approaching plane. Various anecdotal observations (i.e. raptors initial response often begins with what appears to be a head-on defensive response attack flightpath before altering to an evasive flight direction) further support the postulated theory that various species will exhibit differing behaviors and $\boldsymbol{D p b}$. A limited number of head-on interactions with the $\boldsymbol{P A R 4 6}_{\boldsymbol{U V L E D}}$ landing light $\boldsymbol{O N}$ were recorded where organized V-shaped geese flocks would split and fly in opposing directions, or even reverse their flight direction. The agricultural pilot observed that when encountering foraging duck species in the fields during chemical applications with the AirTractor 802 configured with standard blinking 'wing-wag' landing lights, they would usually move a short distance but would be slow in leaving the area. The foraging duck behavior was different when the AirTractor 802 configured with PAR46 $_{\text {UVLED }}$ was turned $\boldsymbol{O N}$. The foraging duck species would usually leave the area after the first fly. The reaction of very large well-organized flocks of geese tended to react as individuals when illuminated by the PAR46 $\boldsymbol{P I V L E D}$ but quickly regrouped the flock structure when they exited the field of illumination.


Figure 17. Illustration of airspace separation between the plane and the birds
This project is the first to study wild birds in a natural environment interacting midair with an aircraft and measure the difference in the bird's distance of response to an approaching plane, operating at a nominal speed of 150 kt with $\boldsymbol{P A R 4 6} \boldsymbol{U}_{\text {ULED }}$ landing lights $\boldsymbol{O N}$ versus $\boldsymbol{O F F}$ resulting in increased flight path separation (see Figure 17). A statistical correlation of predictable distance of response to a three-variable model representing a bird's eye visual capture ability of the plane, the retinal neural coding ability, and the complex nonlinear neural response of the brain to the visual input suggested by recent advances in knowledge of avian vision was established. When the birds were illuminated by the PAR46 $\boldsymbol{P I V L E D}^{\boldsymbol{O N}}$, a stronger behavioral response was seen at a greater distance than when the lights were $\boldsymbol{O F F}$. For a plane traveling at $77 \mathrm{~m} / \mathrm{s}$, the mean reaction distance with the $\boldsymbol{P A R}^{\boldsymbol{P A}} \boldsymbol{U}_{\boldsymbol{U V L E D}} \boldsymbol{O F F}$ is 199.8 m , compared to the $\boldsymbol{P A R 4 6}_{\boldsymbol{U V L E D}} \boldsymbol{O N}$ mean reaction distance of 152.7 m . In this study the maximum distance in which the $\boldsymbol{P A R 4 6}_{\boldsymbol{U V L E D}} \boldsymbol{O N}$ caused the birds to react was 1334 m compared to PAR46 $\boldsymbol{P H V L E D}^{\text {P }}$ OFF distance of 296 m .

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## A Field data and derived values




| 2 | 2.7 | 64.4 | GH020012 1 | 4/19/2012 | 183 | 58 | 7.0 | 1650 |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 1.3 | 2.7 | 121.8 | GH0627161 | 5/6/2021 | 211 | 66 | 3.0 | 1400 |  |
| 1.6 | 2.5 | 78.3 | GH040147 4 | 3/2/2021 | 46 | 44 | 7.0 | 700 |  |
| 1.3 | 2.5 | 110.4 | GH040012 5 | 4/12/2021 | 177 | 63 | 3.0 | 1650 |  |
| 0.7 | 2.4 | 147.9 | GH012711 | 4/28/2021 | 197 | 74 | 9.0 | 700 |  |
| 0.8 | 2.3 | 124.5 | GH020019 4 | 1/20/2021 | 21 | 50 | 7.0 | 1400 |  |
| 1 | 2.3 | 100.1 | GH080152 O | 3/8/2021 | 70 | 42 | 3.0 | 1650 |  |
| 0 | 2.2 | 165 | GH040007 7 | 4/8/2021 | 167 | 60 | 10.0 | 1650 |  |
| 1.6 | 2.1 | 46 | GH020012 1 | 4/12/2021 | 174 | 63 | 3.0 | 1650 |  |
| 0.5 | 2 | 115.5 | GH020179 2 | 3/22/2021 | 137 | 72 | 7.0 | 1100 |  |
| 0.7 | 2 | 113.1 | GH022704 O- | 3/29/2021 | 145 | 72 | 7.0 | 1650 |  |
| 0.6 | 1.9 | 113.1 | GH020036 1 | 5/11/2021 | 213 | 53 | 4.0 | 1100 |  |
| 0.9 | 1.8 | 73.8 | GH020179 1 | 3/22/2021 | 140 | 72 | 7.0 | 1100 |  |
| 0.7 | 1.8 | 95.7 | GH012705 5 | 3/29/2021 | 146 | 72 | 7.0 | 1650 |  |
| 0.4 | 1.7 | 113.1 | GH012703 1 | 3/29/2021 | 141 | 72 | 7.0 | 1650 |  |
| 0.8 | 1.6 | 69.6 | GH012703 1 | 3/29/2021 | 142 | 72 | 7.0 | 1650 |  |
| 0.35 | 1.4 | 80.85 | GH020180 3 | 3/22/2021 | 142 | 72 | 7.0 | 1100 |  |
| 0.7 | 1.3 | 55.2 | GH030152 2 | 3/8/2021 | 64 | 42 | 3.0 | 1650 |  |
| 0.1 | 1.1 | 78 | GH010150 5 | 3/4/2021 | 55 | 44 | 7.0 | 1650 |  |
| 0.1 | 1.1 | 78 | GH010150 1 | 3/4/2021 | 57 | 44 | 7.0 | 1650 |  |
| 0.7 | 1.1 | 34.8 | GH012703 1 | 3/29/2021 | 148 | 72 | 7.0 | 1650 |  |
| 0.6 | 1 | 34.8 | GH012703 1 | 3/29/2021 | 153 | 72 | 7.0 | 1650 |  |
| 0.1 | 0.9 | 73.6 | GH020012 1 | 4/12/2021 | 173 | 63 | 3.0 | 1650 |  |
| 0.4 | 0.8 | 36.8 | GH010012 1 | 4/12/2021 | 172 | 63 | 3.0 | 1650 |  |
| 0 | 0.6 | 52.2 | GH010007 6 | 4/8/2021 | 162 | 60 | 10.0 | 1650 |  |
| 0.4 | 0.6 | 17.4 | GH0600189 | 4/22/2012 | 185 | 52 | 3.0 | 1650 |  |
| 0.2 | 0.4 | 17.4 | GH020034 4 | 3/8/2021 | 82 | 66 | 9.0 | 1650 |  |
| 0.1 | 0.4 | 27.6 | GH040001 1 | 3/30/2021 | 150 | 59 | 9.0 | 1650 |  |
| 0 | 0.35 | 29.05 | GH01019-1 | 1/18/2021 | 11 | 50 | 7.0 | 1650 |  |
| 3.3 | 4.5 | 104.4 | GH050026 1 | 2/24/2021 | 26 | 62 | 9.0 | 1400 |  |
| 5.6 | 6 | 38.8 | GH020038 - | 3/12/2021 | 98 | 58 | 6.0 | 700 |  |
| 7.3 | 10.1 | 243.6 | GH050026 1 | 2/24/2021 | 25 | 61 | 9.0 | 1400 |  |
| 3.2 | 4.5 | 126.1 | GH010038 1 | 3/12/2021 | 97 | 58 | 6.0 | 700 |  |
| 1.6 | 1.9 | 25.5 | GH050026 1 | 2/24/2021 | 27 | 62 | 9.0 | 1100 |  |
| 0.8 | 1.6 | 68 | GH060026 1 | 2/24/2021 | 28 | 62 | 9.0 | 1100 |  |
| 0.7 | 1.6 | 82.8 | GH010005 3 | 4/5/2021 | 154 | 63 | 12.0 | 1650 |  |
| 4.1 | 6.2 | 193.2 | GH030161 | 3/12/2021 | 113 | 60 | 7.0 | 700 |  |
| 3 | 3.9 | 78.3 | GH010025 1 | 4/28/2021 | 192 | 74 | 9.0 | 1100 |  |
| 1.05 | 3 | 97.5 | GH010159 5 | 3/9/2021 | 86 | 51 | 7.0 | 1100 |  |
| 1.5 | 1.9 | 36.8 | GH020159 5 | 3/9/2021 | 89 | 51 | 7.0 | 1100 |  |
| 10 | 11.4 | 70 | GH1201873 | 3/24/2021 | 144 | 72 | 7.0 | 1650 |  |
| 6.8 | 9.2 | 180 | GH030160 3 | 3/12/2021 | 109 | 60 | 7.0 | 700 |  |
| 3.2 | 6.9 | 296 | GH030159 1 | 3/9/2021 | 92 | 51 | 7.0 | 1100 |  |
| 5.5 | 6.8 | 119.6 | GH012703 1 | 3/29/2021 | 150 | 72 | 7.0 | 1650 |  |
| 4.6 | 5.6 | 65 | GH020038 1 | 3/12/2021 | 99 | 51 | 7.0 | 700 |  |
| 1.8 | 4.1 | 161 | GH010004 - | 4/5/2021 | 153 | 63 | 12.0 | 1650 |  |
| 7.6 | 11.2 | 144 | GH0200248 | 4/28/2021 | 194 | 74 | 9.0 | 1100 |  |
| 4.5 | 5.5 |  | GH030038 5 | 3/12/2021 | 101 | 58 | 6.0 | 700 |  |
| 2.4 | 3.1 | 64.4 | GH030038 4 | 3/12/2021 | 100 | 51 | 7.0 | 700 |  |
| 1.8 | 2.8 | 92 | GH030038 6 | 3/12/2021 | 103 | 58 | 6.0 | 700 |  |
| 1.2 | 2 | 73.6 | GH030038 5 | 3/12/2021 | 102 | 58 | 6.0 | 700 |  |
| 3.7 | 4.5 | 69.6 | GH020003 - | 4/5/2021 | 156 | 63 | 12.0 | 1650 |  |
| 1.9 | 3.4 | 138 | GH030161 1 | 3/12/2021 | 112 | 60 | 7.0 | 700 |  |
| 1 | 2 | 87 | GH020029 1 | 4/28/2021 | 195 | 74 | 9.0 | 1100 |  |
| 7.7 | 8.1 | 34.8 | GH020032 2 | 4/3/2021 | 204 | 65 | 4.0 | 1650 |  |
| 0.7 | 2.6 | 165.3 | GH0101611 | 3/12/2021 | 104 | 58 | 6.0 | 700 |  |
|  | 2.6 | 52.2 | GH0100311. | 4/30/2021 | 200 | 65 | 4.0 | 1650 |  |
| 0.6 | 2.1 | 138 | GH0301611 | 3/12/2021 | 114 | 60 | 7.0 | 700 |  |
| 0.9 | 1.8 |  | GH0200248 | 4/28/2021 | 193 | 74 | 9.0 | 1100 |  |
| 1.4 | 1.7 | 26.1 | GH050020 5 | 4/26/2021 | 191 | 62 | 10.0 | 1100 |  |
| 0.6 | 1.4 | 65.6 | GH0100311 | 4/30/2021 | 201 | 65 | 4.0 | 1650 |  |
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| 2 | 4.2 | 191.4 | GH030160 1 | 3/12/2021 | 111 | 60 | 7.0 | 700 |  |
| 1.7 | 2.5 |  | GH030020 6- | 4/26/2021 | 188 | 62 | 10.0 | 1100 |  |
| 1.3 | 2 | 60.9 | GH010032 7 | 4/30/2021 | 203 | 65 | 4.0 | 1650 |  |
| 0.7 | 1.4 | 67.9 | GH020020 1 | 4/26/2021 | 187 | 62 | 10.0 | 1100 |  |
| 11.1 | 13 | 165.3 | GH012703 1 | 3/29/2021 | 151 | 72 | 7.0 | 1650 |  |
| 6.3 | 9.2 | 174 | GH080035 8 | 5/5/2021 | 209 | 68 | 4.0 | 1650 |  |
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| 10.010.0 |  |
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| 10.05.0 |  |
| 10.0 |  |
| $\begin{aligned} & \hline 10.0 \\ & \hline 10.0 \\ & \hline \end{aligned}$ |  |
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| 10.010.0 |  |
| 20.0 |  |
| 10.010.0 |  |
| 15.0 |  |
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| 65.495 ON |
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| 10205 |

10.295
2 ON
2.804
ON

| 72.804 ON |
| :--- |
| 98.823 ON |


| 139.19 | ON |
| :--- | :--- |
| 113.122 | ON |


| 113.122 | ON |
| ---: | ---: |
| 89.358 | ON |


| 899358 | ON |
| ---: | ---: | ---: |
| 159.249 | ON |


| 159.249 | ON |
| ---: | ---: | ---: |
| 62.025 | ON |


| 62.025 ON |
| :--- |
| 103.835 ON |
| 101.458 ON |

101.458 ON

| 101.495 |  |
| ---: | ---: | ---: |
| ON |  |
| 70.067 | ON |


| 70.067 |
| :--- | :--- |
|  |
| 85.541 |
| ON |


| 85.541 | ON |
| ---: | ---: |
| 101.447 | ON |


| 67.848 ON |
| :--- |
| 7.361 ON | | 74.361 | ON |
| :--- | :--- |
| 62.337 | ON |

62.337 ON
72.532 ON
72.635 ON
$55.735 \mathrm{ON}^{\circ} \mathrm{ON}$
$55735{ }^{\mathrm{ON}}$

| 55.7.75 |
| :--- |
| 70 ON |
| 70.086 |

75.086 ON
55.959 ON
61.334 ON

| 15.934 ON |
| :--- |
| -1.494 ON |


| 25.633 |
| :--- |
| 44.941 ON |


| -25.033 | ON |
| :--- | :--- |
| 44.941 | ON |
| $45.61 \mathrm{ON}_{2}$ |  |


| 45.651 ON |  |
| :--- | :--- | :--- |
| 93.133 | OFF |


| 56.544 | OFF |
| ---: | ---: |
| 256.060 | OFF |


| 256.062 | OFF |
| :--- | :--- |
| 114.821 | OFF |
| 33488 | OFF |


| 36.448 | OFF |
| :--- | :--- |
| 6.991 | OFF |


| 656.991 | OFF |
| :--- | :--- |
| 75.607 | OFF |


| 75.607 | OFF |
| :---: | :--- |
| 193.601 | OFF |
| 72.654 | OFF |


| 75.601 OFF |
| :--- |
| 72.64 OFF |
| 87.001 OFF |


| 87.0101 OF |
| :--- |
| 55.216 |
| 67.67 |


| 557.2667 | OFF |
| :--- | :--- | :--- |
| 177.410 | OFF |


| 177.410 | OFF |
| :--- | :--- | :--- |
| 320.256 | OFF |

108.002 OFF

| 65.641 | OFF |
| :---: | :---: |
| 154.497 | OFF |



| 1344.648 | OFF |
| :--- | :--- | :--- |
| 82.449 | OFF |


| 82.449 | OFF |
| :--- | :--- | :--- |
| 65.388 OFF |  |
| 82.449 | OFF |

82.449 OFF
69.875 OFF
67.767
OFF

| 69.8757 |  |
| :--- | :--- | :--- |
| 67.765 OFF |  |
| 127.855 | OFF |


| 127.855 | OFF |
| :--- | :--- |
| 77.603 | OFF |


| 78.603 | OFF |
| :--- | :--- |
| 53.479 | OFF |


| 53.479 | OFF |
| :--- | :--- | :--- |
| 159.629 | OFF |
| 61247 | OFF |



| 127.855 | OfF |
| :--- | :--- | :--- |
| 64.816 | OFF |


| 64.816 | OFF |
| :--- | :--- | :--- |
| 35.786 | OFF |


| 35.786 OFF |
| :--- |
| 65.901 OFF |
| 53.479 |


| 55.901 | OfF |
| :--- | :--- | :--- |
| 53.479 | OFF |
| 191.384 | OFF |


| 191.384 | OFF |
| ---: | :--- |
| 62.360 | OFF |


| 62.360 | OFF |
| :--- | :--- |
| 64.012 | OFF |


| 64.012 | OFF |
| :--- | :--- | :--- |
| 66.944 OFF |  |
| 159.629 OFF |  | | 170.113 OFF |
| :--- | :--- | :--- |
| 55.216 OFF |



 | 120.47 |  |
| ---: | :--- |
| 65.012 | OFF |
| 159.629 | OFF |



