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Agile Robust Autonomy: Inspired by Connecting Natural Flight and Biological Sensors

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14. ABSTRACT

The goal of research conducted under work unit W0PY was to understand insect flight for purposes of improving agility, autonomy, robustness, and integrated sensing and processing of unmanned aerial vehicles. This goal was approached using a comparative methodology in order to understand general principles of insect flight across diverse species; understand environmental variables that impact natural flight of insects; understand how insects can recover from flight perturbations; and understand the connection between flight, sensor capability, neural processing, and muscular control.

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1.0 SUMMARY

The goal of research conducted under work unit W0PY was to understand insect flight for purposes of improving agility, autonomy, robustness, and integrated sensing and processing of unmanned aerial vehicles. This goal was approached using a comparative methodology in order to understand general principles of insect flight across diverse species; understand environmental variables that impact natural flight of insects; understand how insects can recover from flight perturbations; and understand the connection between flight, sensor capability, neural processing, and muscular control.

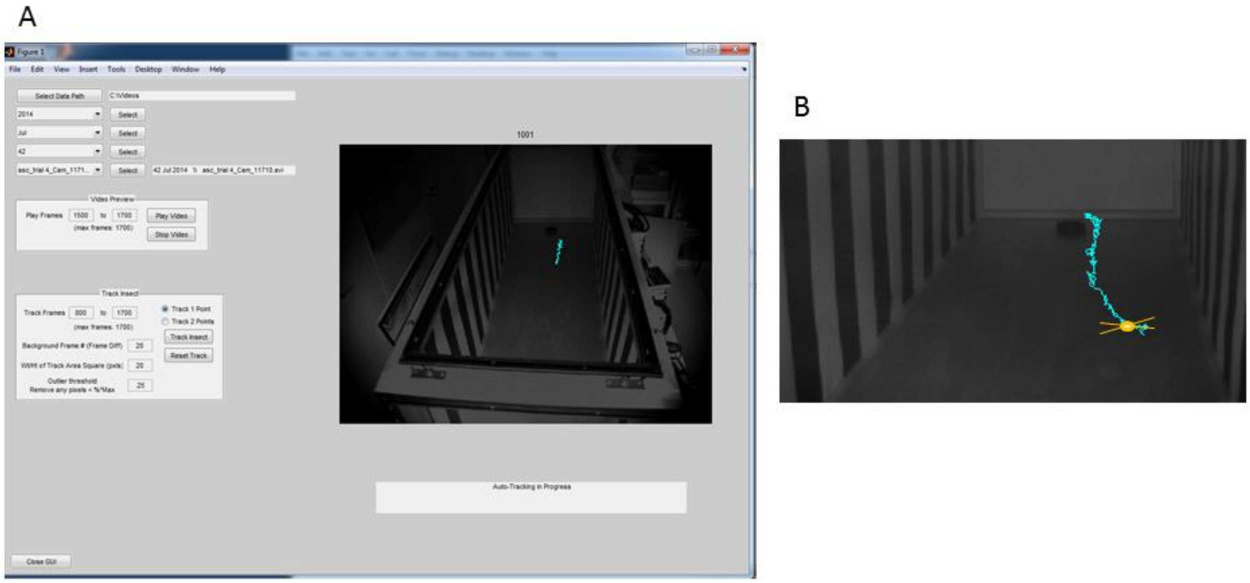
2.0 INTRODUCTION

Insects are existence proofs for agile, robust, autonomous flight that minimizes size, weight, and power requirements, aspects that are desirable for human-engineered systems. To learn design principles for improved sensors and guidance/control algorithms, AFRL studies insect sensors and flight. The current research effort attempts to connect the environmental information with insect flight and relate that to insect sensors and processing. The goal is to understand insect flight for purposes of improving agility, autonomy, robustness, and integrated sensing and processing of unmanned aerial vehicles.

3.0 2014 ANNUAL REPORT

Indoor laboratory and outdoor laboratory flights of insects were recorded by high-speed cameras with frame rates from 500–1000 Hz. Indoor laboratory flights were recorded in a flight chamber measuring 2 m x 1 m x 1 m and lined with different optic flow patterns. Outdoor laboratory flights were recorded by releasing just captured insects in front of high-speed cameras and allowing them to initiate escape flight. The goal was to compare the kinematics of each flight inside the laboratory versus outside in the natural world. This effort required automating the tracking of the insect in the video frames because the dataset captured is extremely large. If using just two cameras recording at 1000 frames per second, the study cameras are capable of recording 8 seconds of data. The insect’s position would need to be found and recorded in 16000 frames for one behavior capture.

David Forester (in-house contractor) started work automating this process based on Ty Hedrick’s algorithms (Hedrick, 2008). Figure 1 illustrates challenges in adapting these techniques indoors. Also shown in Figure 1 are early behavior recordings of Green Darner dragonflies (Anax junius) in this flight chamber by Kaitlin Fair. Kaitlin’s goal was to establish repeatable protocols for eliciting flights in insects large enough to carry a telemetry recoding chip to correlate flight kinematics, responses to optic flow stimuli, and muscle potentials (Harrison, 2011). She has since moved on to studying compressive sensing for her PhD but hopes to return to working on this starting in 2017.



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Auto-Tracking in Progress

Figure 1. **Early tracking results illustrating the difficulty in tracking a small, *not* highly contrasted, unmarked flying insect against a background with changing contrast in an automated (or semi-automated way). A) Screen capture of automated tracking program. B) Trajectory of tracked flying insect in one camera view.**

Outdoor flight recordings have their own challenges, as illustrated in Figure 2. It is also likely that the objective of capturing completely natural kinematics is not being reached, because the insects are manipulated beforehand. Future efforts will move towards completely natural conditions, capturing flight from insects that have not experienced any interference from the research team.

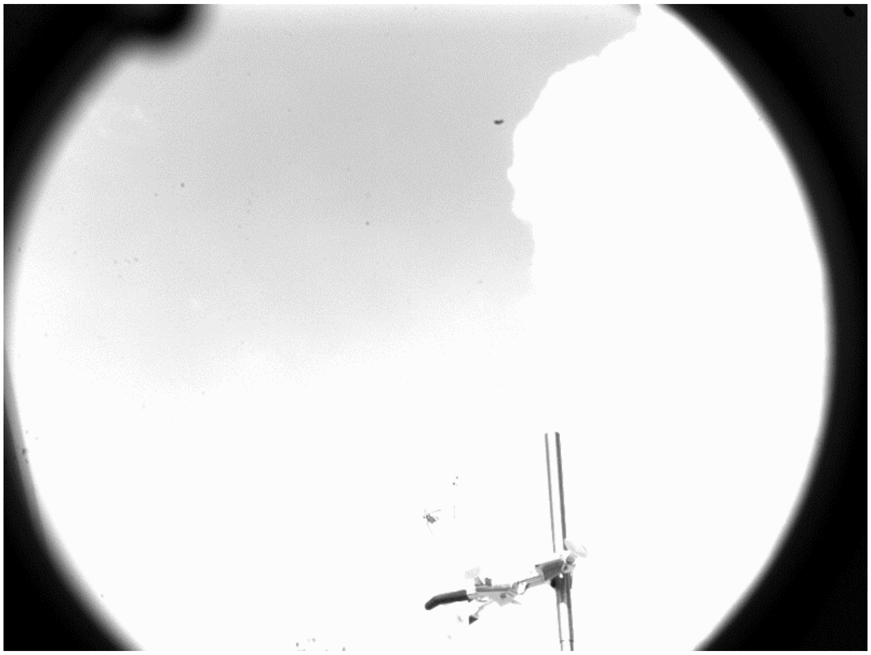

Figure 2. Outdoor recording screenshot of local robberfly (Diogmetes) after capture. Lighting conditions are challenging because of changing weather conditions. The sky is used as a background in an attempt to increase the contrast of the insect and background, The robberfly is directly above the release point in this screenshot.

Gaze stabilization is also of interest, but, as can be seen in Figure 1, the head of the insect is not easily discernable in free flight. In addition, it would be difficult to induce precise behaviors to induce a gaze stabilization response. Therefore, efforts were started toward characterizing gaze stabilization in insects while tethered. The stimulating is a rotating horizon line produced by UV and green LEDs (Figure 2).

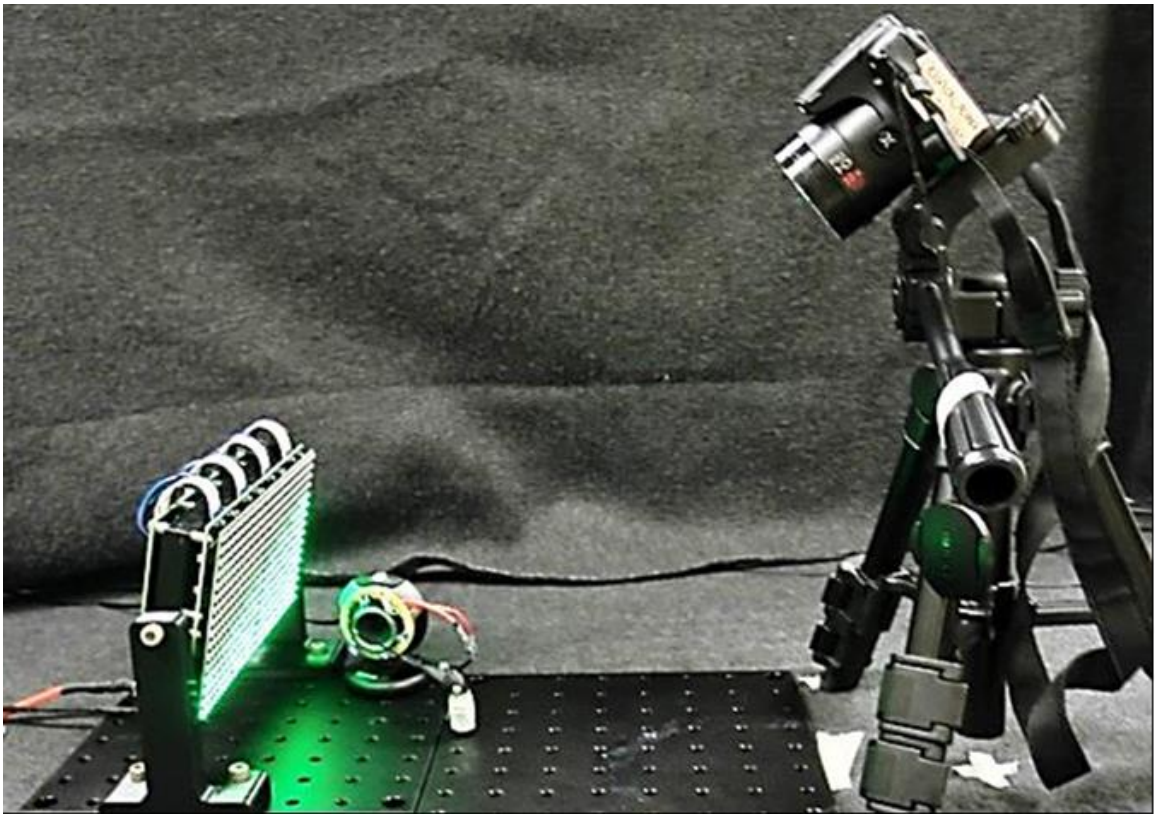

Figure 3. Damselfly gaze stabilization setup. Panel field of view = 45 x 22.5 degrees. Local species of damselflies, robberflies, and dragonflies have all been tested in this apparatus and have failed to respond with head rotations.

4.0 2015 ANNUAL REPORT

4.1 Stabilization of the head in flight

Blowflies stabilize in flight by moving their heads and bodies (Hengstenberg 1993). The visual system plays a role in this multi-sensory task. Previous work has shown that insects can reduce motion blue and maintain consistent visual perception by moving their head independently of their body by employing a head stabilization reflex which is a control loop that rolls the head with respect to the visual environment (Goulard et al 2015). This has been studied in honeybees (Boeddeker 2009), wasps (Viollet 2013), and flies (Krapp 2012) most often using an edge as visual stimulation to a tethered insect.

A projector dome with a field of view of 240 x 120 degrees (Figure 2) was used to stimulate tethered Ischnura ramburii damselflies (Figure 1). Early recordings used stimulation that was readily available—cityscapes that were already mapped onto the dome in correct perspective (Figure 3). In order to standardize responses, a horizon scene was built that could be rotated at a user-defined speed, transversing a user-defined angle (Figure 4).

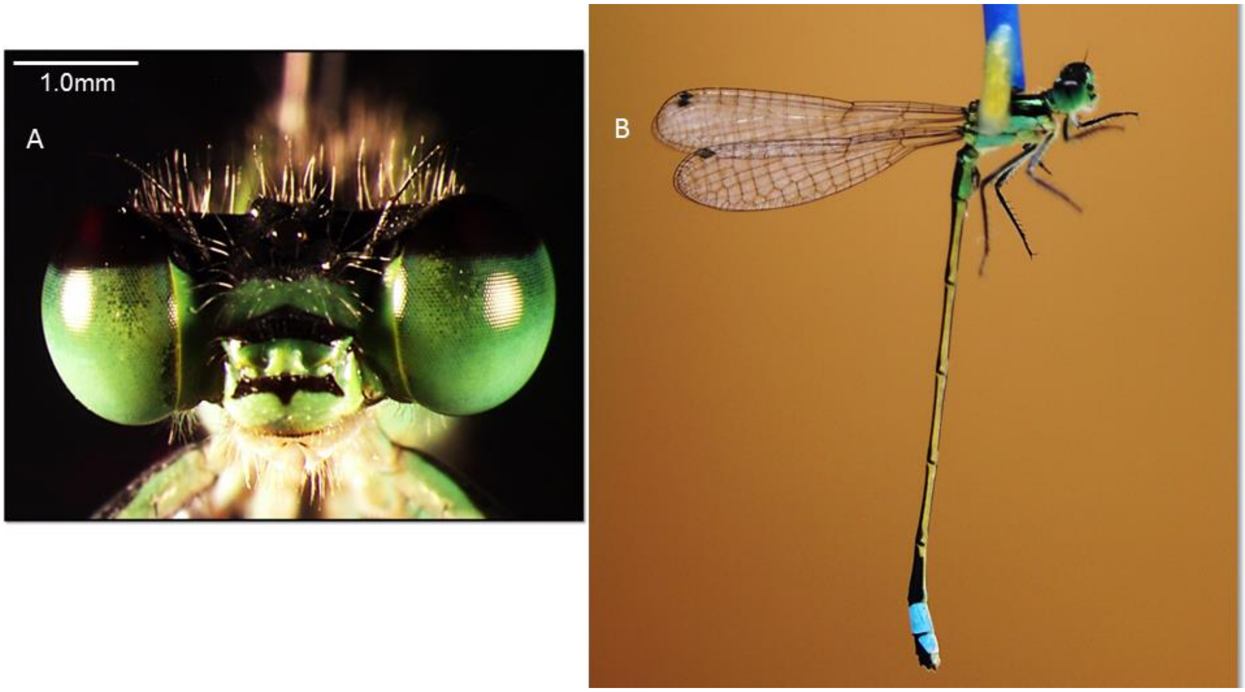

Figure 4. Head of a damselfly showing compound eyes and ocelli clearly. B) Tethered damselfly.

Figure 5. **Visible wide field of view projector for stimulation of gaze stabilization response in insects. Field of view = 240 x 120 degrees.**

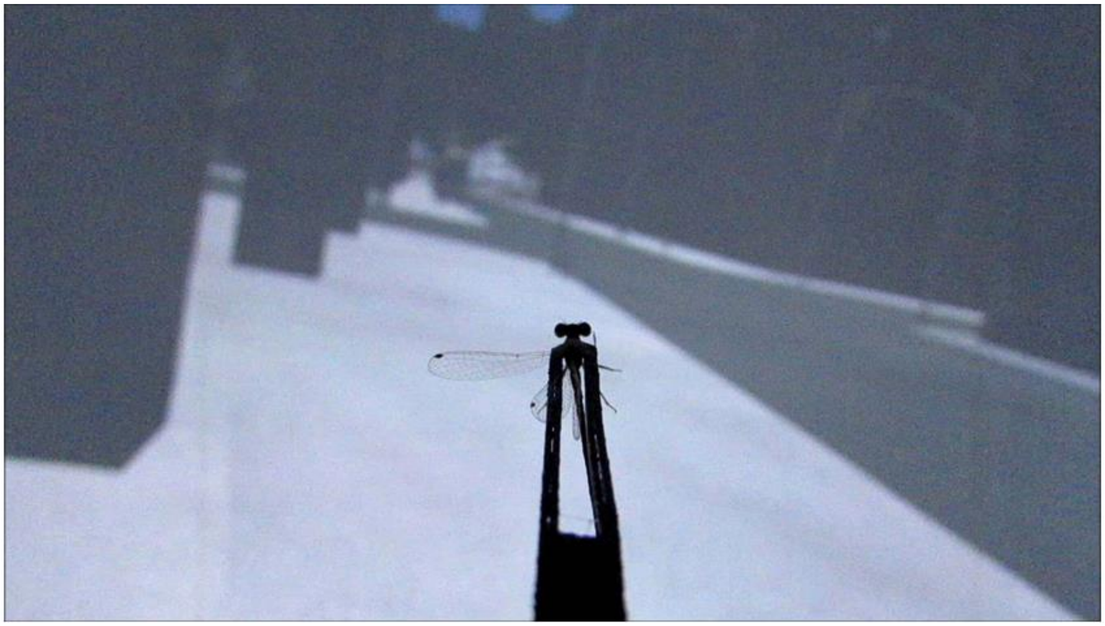

Figure 6. **Initial stimulation for damselflies in dome with field of view = 240 x 120 degrees.**

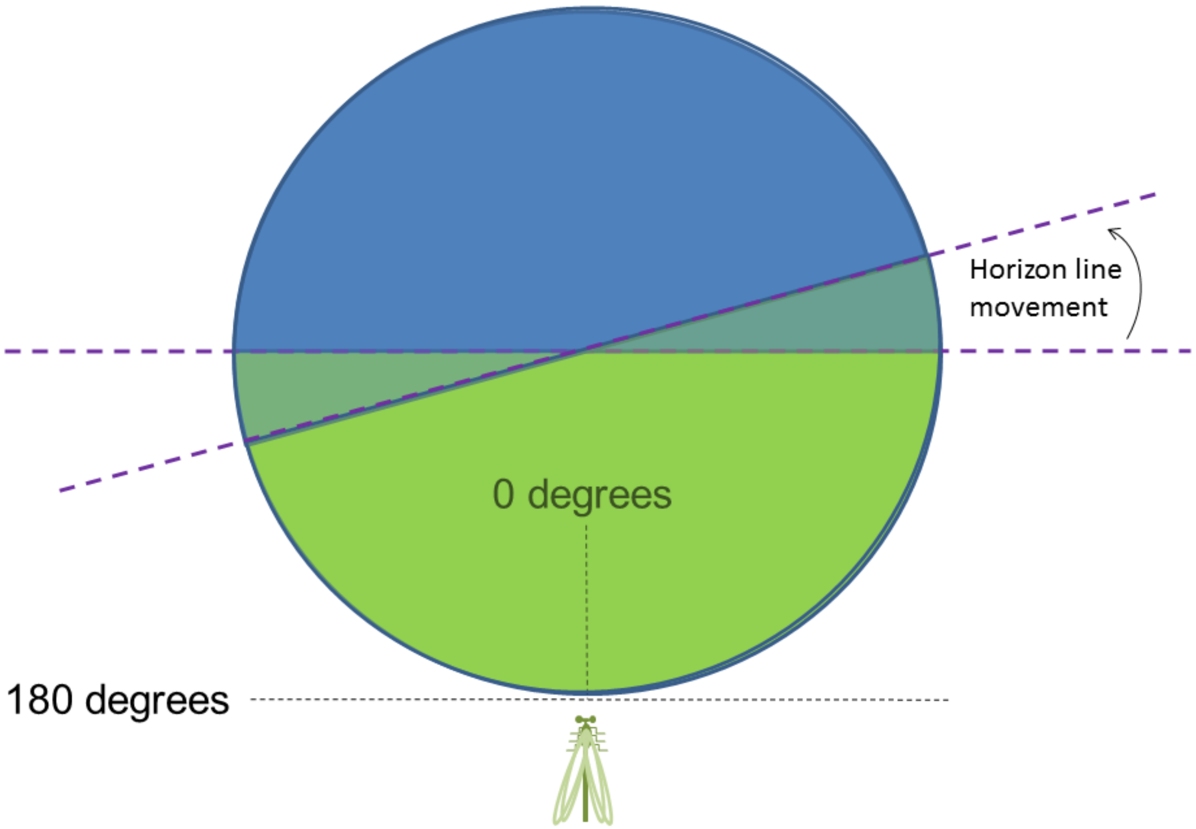

Figure 7. **Designation of reference frame for visual stimulation.**

The movement of the damselflies was recorded using high-speed cameras. Work is now ongoing to quantify the head rotation and body positions from the videos (Figure 5).

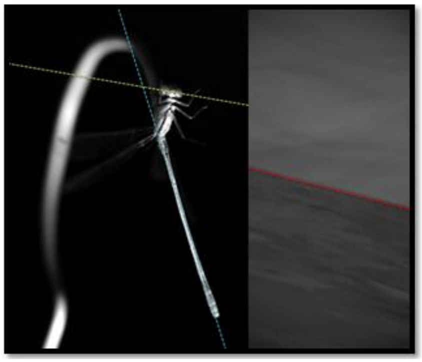

Figure 8. **Tethered damselfly in the dome, screenshot of a high-speed recording. Lines illustrate desired measurements.**

In 2015, we manipulated the bounds of the rotating horizon scene. We established at what angular extent a center disk that blacked out the center of the scene stopped the gaze stabilization response in a damselfly (Figure 6). Then we established the angular bound of blacking out cone in stopping a stabilization response (Figure 7). Combing these measurements, we tested a ring of rotating horizon to establish whether this could elicit a stabilization response (Figure 8). These experimental treatments were repeated for 14 damselflies of the same species (mixed gender) and the results were found to be consistent over individuals.

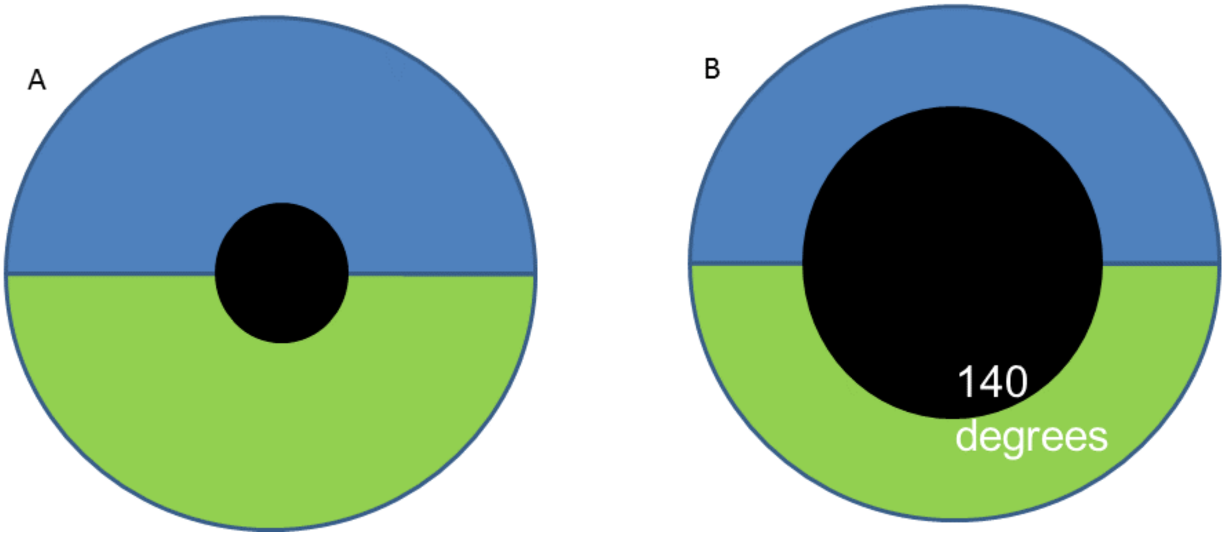

Figure 9. Radius of blacked-out center is enlarged until animal stops responding. A) Less than 140 degrees, animal still responds with head rotation. B) At radius of 140 degrees, animal stops responding. [not to scale]

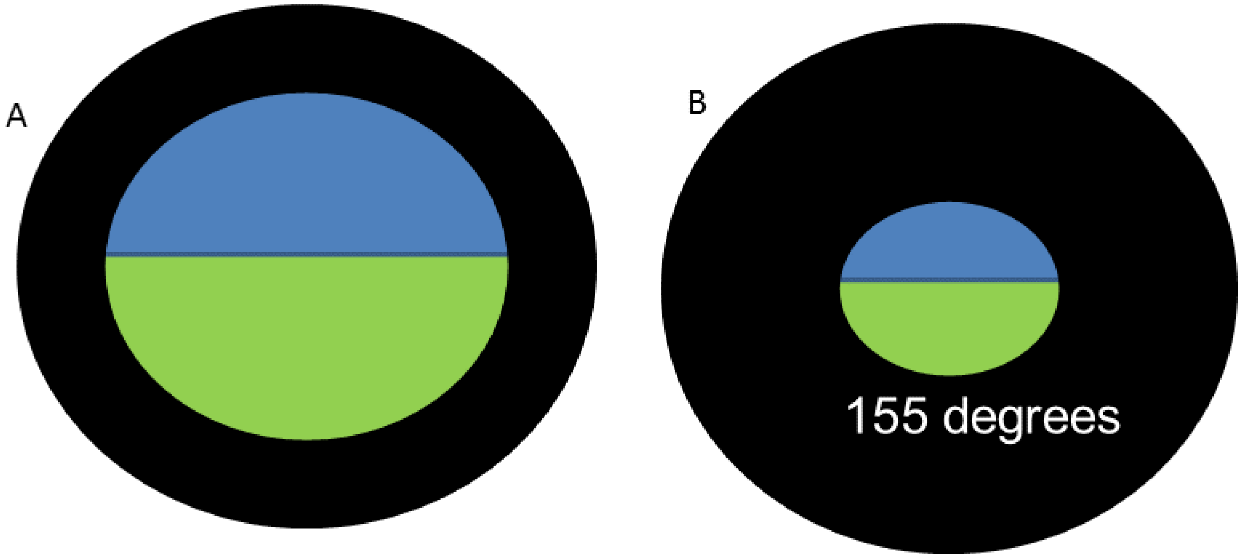

Figure 10. Radius of blacked-out “cone” is enlarged until animal stops responding. A) Greater than 155 degrees, animal still responds with head rotation. B) At radius of 155 degrees, animal stops responding.

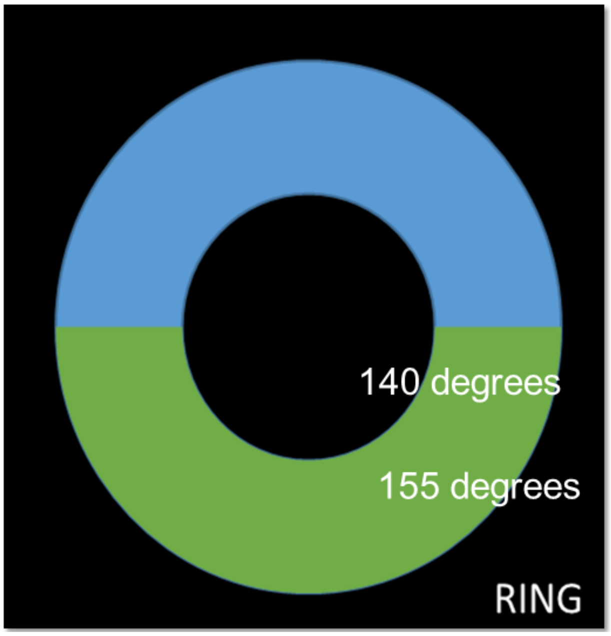

Figure 11. Ring of stimulation sufficient and necessary for head movement response to rotating horizon.

There are three hypotheses to explain the consistent response in Figure 8. First, the rotation the horizon undergoes in the center is different than at the edges of the dome (Figure 9A). At the edges of the dome, the horizon sweeps a larger area than in the center. This also means the horizon is rotating at a different speed at the edges of the dome than at the center. The damselflies could have a particular rotation extent or frequency that they respond to for stabilizing their gaze. Rotations above and below this frequency or extent would not elicit this response.

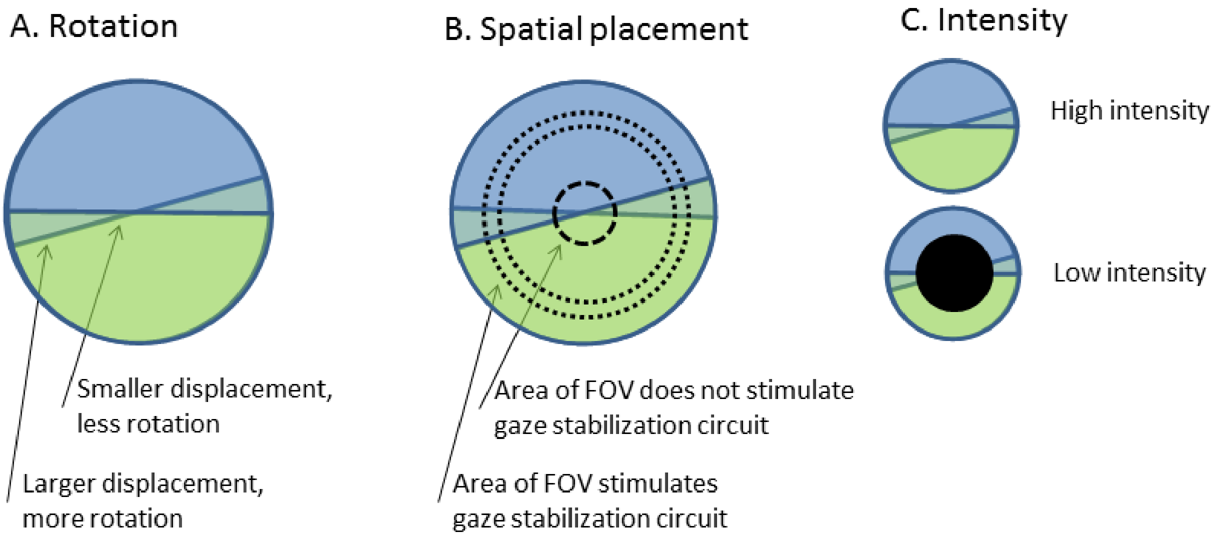

Figure 12. Hypotheses to explain behavioral response. A) Both the speed of the horizon and the spatial extent of the horizon movement change from the center to the edges. B) The field of view that stimulates the gaze stabilization circuit is in the periphery and not in the center. C) The intensity is decreased when areas are blacked out, and the animal stops responding when intensity it too low.

The second hypothesis to explain the response in Figure 8 is that the damselfly optical processing circuitry uses a portion of the field of view of the eyes for gaze stabilization (Figure 9B). The compartmentalization of this response might correspond to differences in the resolution of the compound eye. For example, the upward looking part of the compound eye might have increased resolution to look and track prey items while the periphery would be used to track large scale motion of the visual field and stabilize the visual sensors.

The third hypothesis to explain the response in Figure 8 would be that blacking out portions of the field of view reduces the overall intensity of stimulation to the eyes of the damselflies and therefore decreases the response accordingly (Figure 9C). The damselfly optical system would have a threshold of light needed to utilize their gaze stabilization circuitry. It is possible that blacking out portions of the field of view reduces the light to levels below which the damselflies cannot respond to the moving horizon.

In 2016, these three hypotheses (Figure 9) were tested by manipulating the horizon scene in ways to eliminate these confounding explanations (Figure 10) for rotation, spatial placement, and intensity. In addition, the experiment was expanded to include the following:

- Determine behavioral response to vertical extent of stimulus.
- Determine behavioral response threshold to texture in scene.
- Spectral ERG of damselfly eyes, compound and ocellar.
- Alternatively occlude ocelli and compound eyes and perform behavior tests again.
- Test other insects for similar response:
    - Dragonflies
    - Robberflies, and
    - Relatives of the ***Ischnura ramburii*** damselfly.
- Measure the field of view of the compound eyes and ocelli.

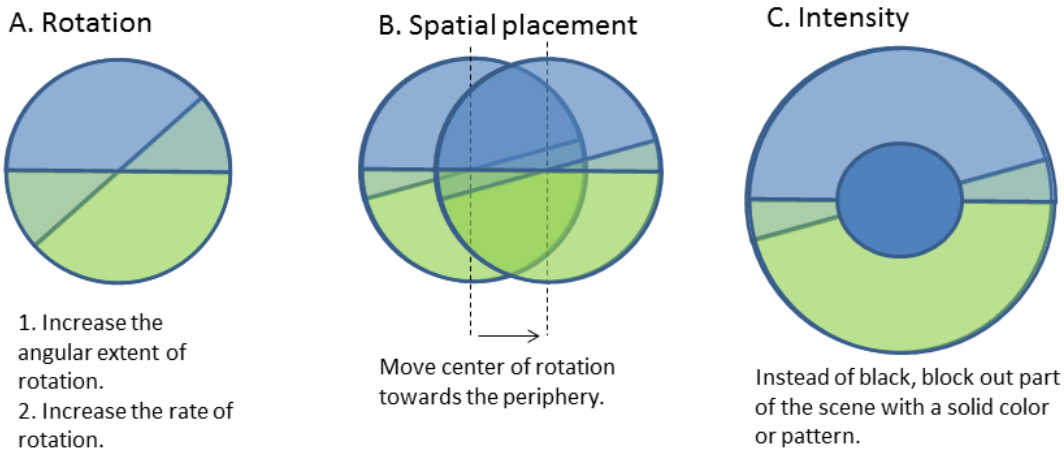

Figure 13. Testing hypotheses to explain behavioral response. A) Response zone will shift to match a particular rotation speed or spatial displacement of the horizon line. B) The field of view that stimulates the gaze stabilization circuit remains stable as center is shifted. C) The response zone will change size based on total intensity of the scene.

4.2 High-speed Recordings of Natural Flight during Very Low Light Conditions

High-speed recordings were attempted at night of natural flight near light collection setups (Figure 11). LED panels emitting light in the infrared were used on the ground pointing skyward next to a light sheet reflecting UV light. The hope was that the UV light would attract flying insects. The insects would fly through the infrared light from the LED panels in front of the high-speed cameras. We would then be able to record the natural flight of these insects without manipulating them. This proved to be challenging in execution and no usable flights were captured.

Figure 14. High-speed videography setup attempt at night collecting station.

4.3 Challenges to Auto-Tracking Insects

Automation saves an enormous amount of man hours therefore saving money. There are multiple challenges to tracking insects in video recordings:

- Dim light
- Complex backgrounds
- Small subjects
- Unmarked subjects
- Arbitrary camera angles, insect flies directly towards camera on focal axis

A summary of tracking efforts by Eglin so far include the use of Ty Hedrick's code. State of the art automated tracking software has been developed in Tyson Hedrick's lab. It is the field standard, and it is easy to use with markers and large specimens. It uses one-point tracking per specimen but can track multiple specimens. In-house code efforts were started with David Forester (in-house contractor) and enabled basic, automated tracking for 2D of insects using two-point tracking. This was better than Hedrick's code of one-point tracking because it enabled us to obtain body axis measurements. David Forester took a job at another facility. Kaitlin Fair (government personnel) then expanded the user interface and contrast conditions for 2D tracking of insects. Kaitlin is now working on her PhD at Georgia Tech. David Richards (in-house contractor) has accomplished the calibration of multiple cameras (based on Ty Hedrick's code), combined multiple 2D for 3D coordinates of insects. He has also compared Trevor Wardill's code developed to track killer flies in small, brightly lit space at Oxford. David Richards has also utilized a simulation to compare different methods for accuracy; this simulation is called IRMA. IRMA is a simulation tool designed in-house, and development continues via contractors. It slows construction of imagery/movies of scenarios for different sensors using a visible static camera as sensor. The scene built by David Richards consists of a floor and tabletop along with a moving, 1 cm cube that represents the flying insect (Figure 12).

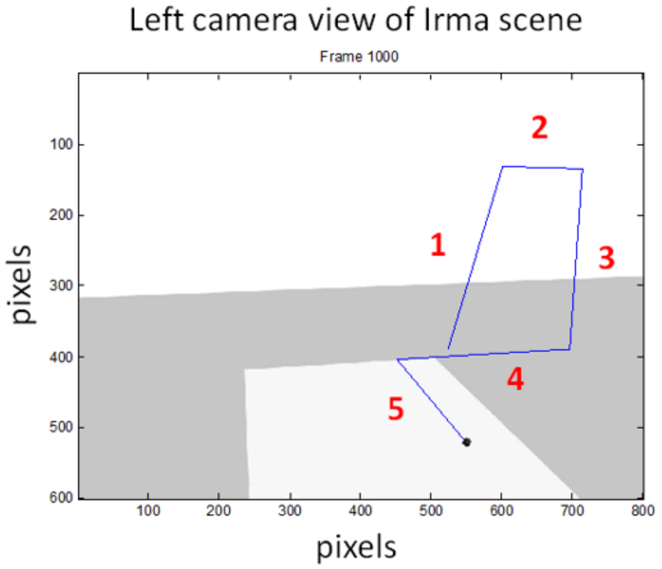

Figure 15. The scene consists of a floor and tabletop along with a moving, 1 cm cube which represents the flying insect. The cube's trajectory consists of 5, 200-frame segments.

Three sources of error have been identified in auto-tracked trajectories including quantization error, localization error, and data association error (Figure 13). Ty Hedrick tested quantization error with different camera positions in simulation (Theriault, 2014). Tested localization error by adding noise in simulation. Tested data association error in hardware testing by throwing an object and using gravity and mass to check. They state their error as being less than body length of a bat and half the body length of a bird. This would be several body lengths of an insect. For insects, especially when looking at accelerations where errors are integrated twice, a goal would be to reduce the error.

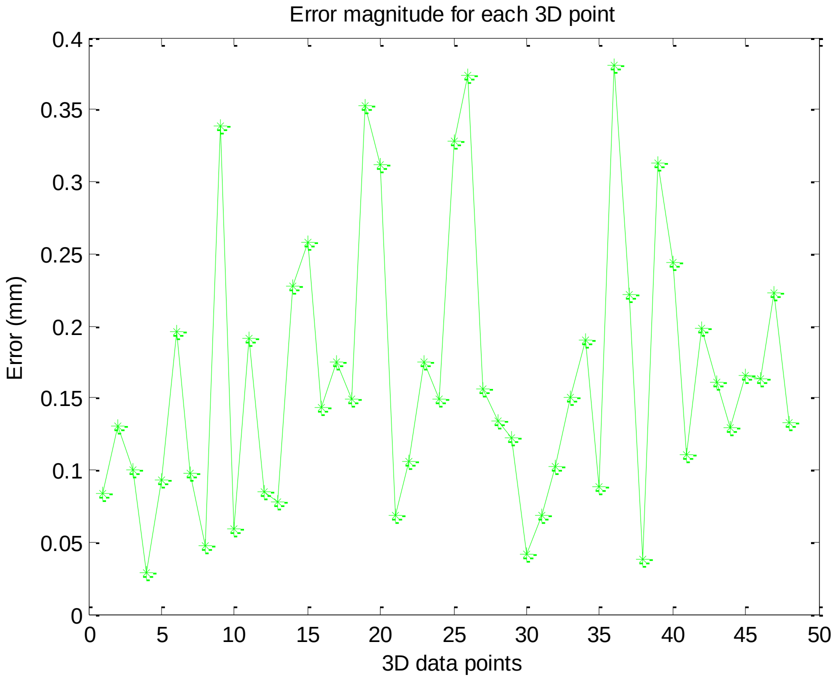

Figure 16. Graphical Calibration Error Results

Using IRMA confirms error estimated looking at different camera positions and adding noise. The goal would be to explore when and how different algorithms fail, and examples would be multiple moving objects, moving object and moving background, and/or background changing contrasts. Also, we would like to explore observation distance, pixels on target, and measure position error. We question whether it would it be possible to define a requirement for maximum observation distance and minimum pixels on target to obtain an acceptable position error (Figure 12).

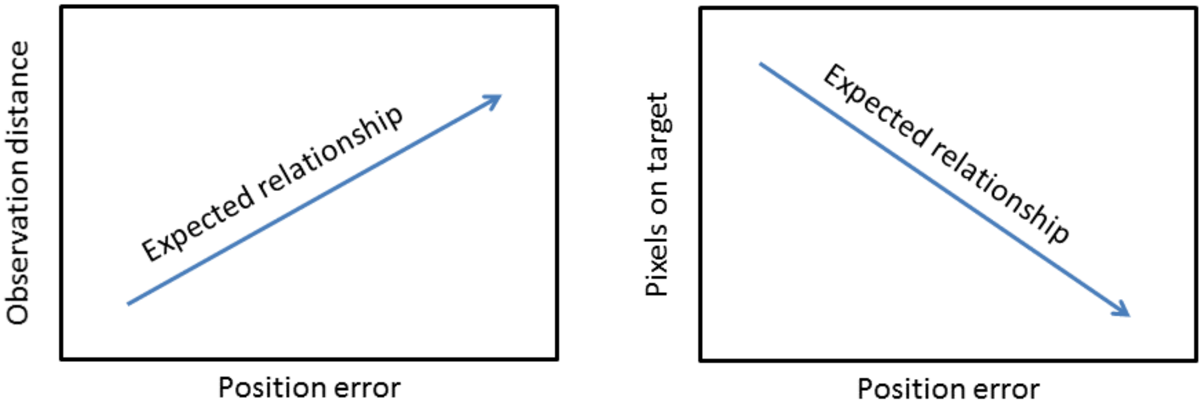

Figure 17. Projected relationships between position error (measured) and observation distance and pixels on target (user defined).

5.0 2016 ANNUAL REPORT

5.1 Outdoor Completely Natural Flight Capture

Figure 18. Natural outdoor flight recording setup

Multiple completely natural high-speed recordings of flying insects were attempted (Figure 1). We chose to focus on damselflies to complement the gaze stabilization work (Figure 2). It would be useful to tether insects at a natural body angle, but this element is not yet known. A screenshot of one of these recordings illustrates the challenges faced by auto-tracking algorithms (Figure 2). The damselflies do not always present a high contrast to the background. The background is also being moved by the wind and is not constant. We are still working on automating the tracking of insects in these natural conditions (Figure 3).

Figure 19. Damselflies in natural flight outdoors with complex and changing background due to wind. Screenshot of high-speed recording.

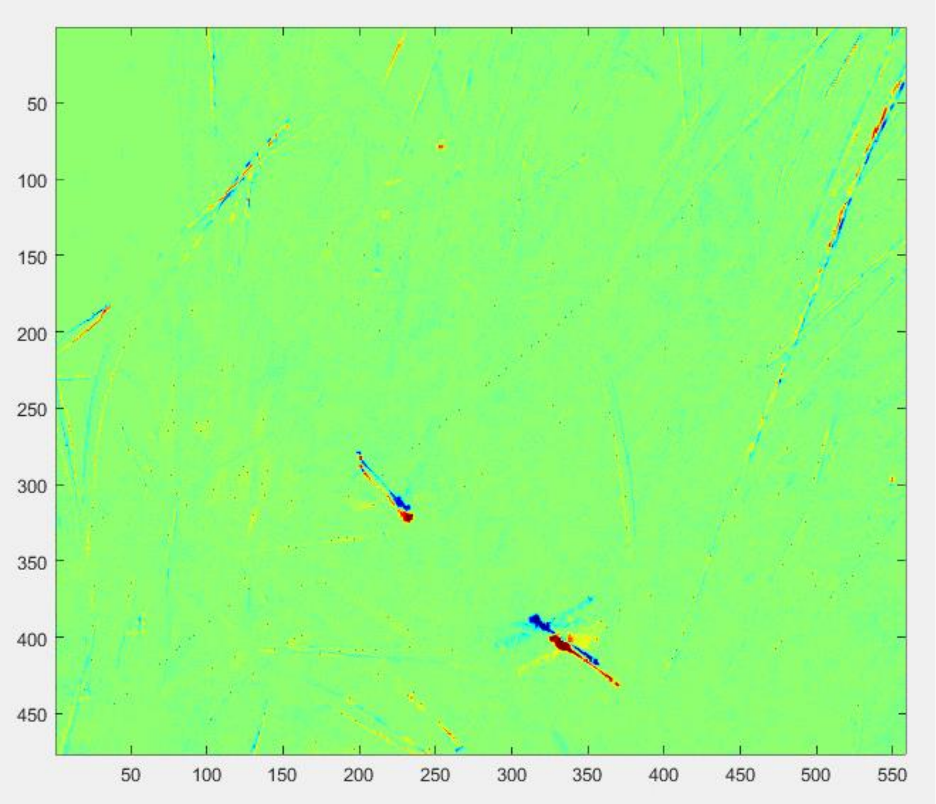

Figure 20. Auto-tracking example of outside flight recordings of damselflies. Movement over five frames. The blue is where the insect is now; red is where it was five frames ago.

5.2 Gaze Stabilization of Tethered Damselflies

For technical reasons, we chose to test the intensity hypothesis to explain the gaze stabilization response found in 2015. Teal would be used, instead of black, to block out portions of the field of view of tethered damselflies and the angular position of these bounds noted when the damselflies stopped responding with stabilization movements (Figure 4). This would either increase the intensity or leave it unchanged. However, the dome material was changed because the old fabric was tearing and the projection system updated and recalibrated. The damselflies did not respond to the new system. We switched to the old fabric but were unable to switch to the old projection system. We therefore needed to try to repeat 2015 experiments in addition to the teal bounds. We successfully obtained five individuals that would respond to the horizon with stabilization movements, but the results were not the same as last year (Table 1). Instead of a ring of stimulus resulting, the bounds of the disk and cone overlap. Further testing is required before these results can be interpreted.

Table 1. Degree responses of individuals tested with black and teal bounds.

	Black Bounds		Teal Bounds	
Specimen	**Cone**	**Disk**	**Cone**	**Disk**
1	130	100	110	130
2	110	90	90	120
3	110	90	110	110
4	120	90	120	110
5	120	90	130	90

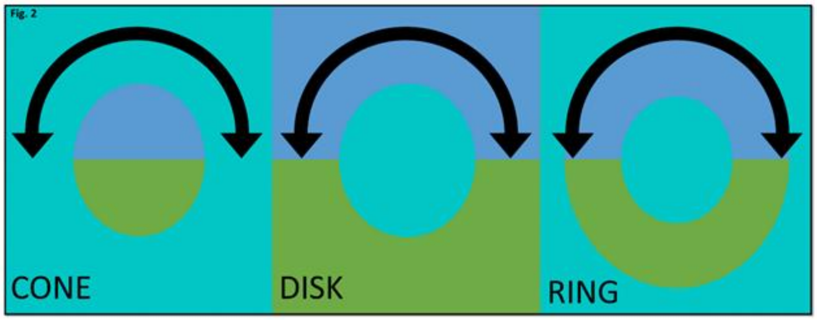

Figure 21. Dome visual stimulation for damselflies. Teal is used to block out the rotating horizon line.

5.3 Electroretinography (ERG) of Damselfly

ERGs are field potential recordings from the eyes. In the damselflies, we recorded from the compound eyes. The stimulation is a xenon light lamp producing light from the UV to near IR wavelengths. A monochromator and neutral density filters allow the same number of photons to be selected at a particular wavelength to be used as spot stimulation onto the eye. An electrode in the eye is used to record the voltage response. The voltage response is then compared to a baseline, and the on/off responses are measured (Figure 5). In addition, a green LED is used between every wavelength measurement to assess the accommodation of fatigue of the individual under study.

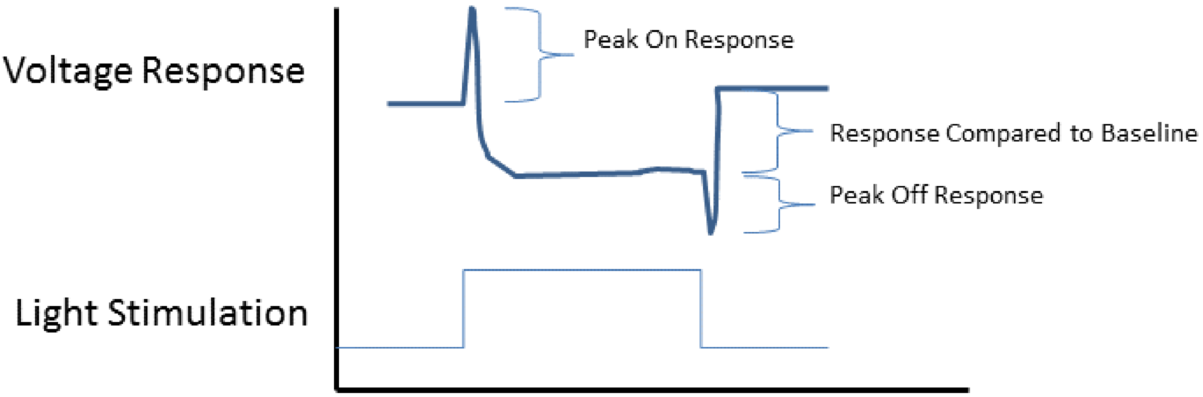

Figure 22. **Analysis of voltage response using electroretinography recording of damselfly compound eye.**

An ERG of the damselfly illustrates that it is sensitive to most of the visible spectrum in addition to UV (Figure 6 left-hand panels). The green LED does not illicit a consistently decreasing response over experimental time (Figure 6 right-hand panels), and therefore we can conclude that the spectral response is not confounded with accommodation or fatigue of the insect. The strength of the response in red was what we were hoping to find. The KHILS dome has a strong red component to the horizon scene in the ground (Figure 7). In the future, it would be useful to look for spectral differences as a function of location in the eye, e.g., dorsal vs. ventral. Future testing would also include testing linear polarization sensitivity as a function of location in the eye.

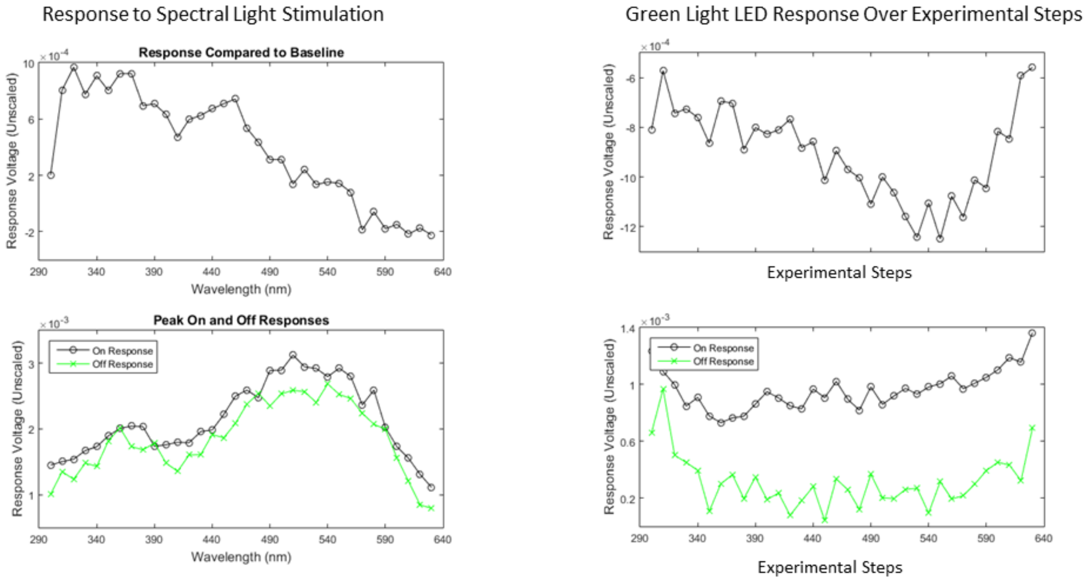

Figure 23. **ERG recordings from the damselfly to spectral light in addition to a green LED. One green light LED recording was taken after each spectral measurement.**

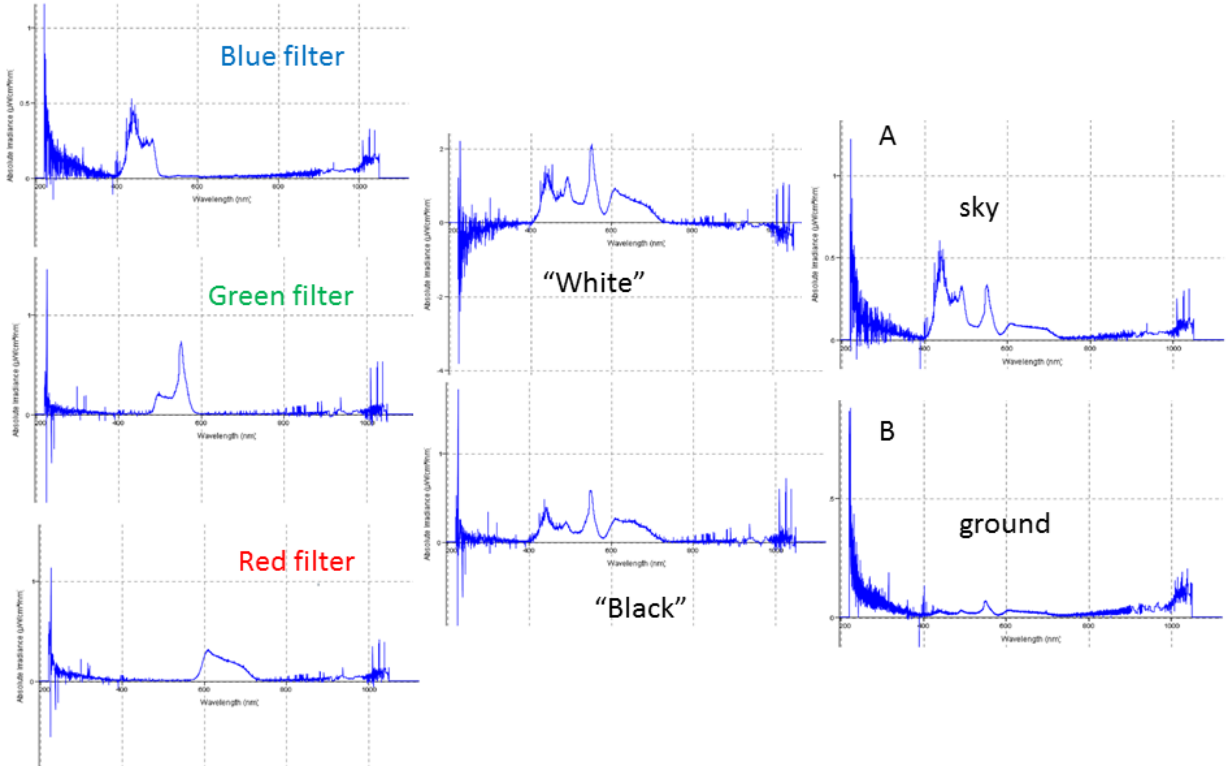

Figure 24. KHILS Projector Spectral Characteristics. A) Ocean spectrometer measurement of the projected sky in KHILS bio-dome. B) Ocean spectrometer measurement of the projected ground in KHILS bio-dome.

5.4 Compound Eye Resolution of Damselfly

Attempted measurements using a highly automated goniometer instrument called FACETS (Douglass 2016) showed some change in facet size over the compound eye of a damselfly (Figure 8). In the future, when measurements are complete, we will use them to make a 3D model (lens size and 3D position). That model will then: 1) map the compound eye to KHILS dome and know where each facet is looking, 2) project what each facet actually sees, and 3) allow us to project selectively to each facet.

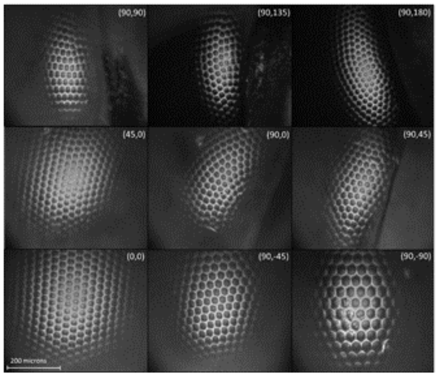

Figure 25. Measure ommatidial lens array with FACETS.

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