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Published in:
The Journal of Engineering

2019

Citation for published version (APA):
Brydegaard Sorensen, M., & Jansson, S. (2019). Advances in entomological laser radar. In *The Journal of Engineering* Institution of Engineering and Technology.

Total number of authors:
2

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Conference Paper · October 2018

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ADVANCES IN ENTOMOLOGICAL LASER RADAR

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Keywords: Laser Radar, Biophotonics, Remote Sensing, Pest Monitoring, Entomological Ecology

Abstract

During last decade we have developed and applied optical remote sensing instrumentation for *in situ* remote surveillance and quantification of the aerofauna. The sparse structure of aerofauna makes optical focusing challenging, but we solved this issue through applying the century old Scheimpflug condition. With this approach we have managed to reduce size, cost and complexity of atmospheric lidars and accomplished an effective tool for ecological entomology capable of counting thousands of insects per hour. Because of the high sensitivity and resolution in time and space, we can retrieve target modulation signatures in the kHz range for target classification purposes. As opposed to the cm waves in entomological radar, we rely on near infrared light around one micron. This allow superior beam quality, negligible ground clutter and applications close over ground or within vegetation structure. Near infrared light can assess both molecular and microstructural properties of the target through differential absorption and depolarization. Here we give the background of entomological lidar, summarize our recent progress and put it in context with contemporary work. We outline applications, ongoing activities and state of the art. We discuss future prospects and challenges.

1. Background

Following WWII development of radar, radar ornithology[1,2] and later radar entomology[3,4] emerged in the last century. This century entomological lidar emerged[5-8] with time-of-flight lidars at kHz rates developed in Montana. Our group in Lund started out using a slower atmospheric lidar at hand[9-12] in particular explorer feasibility of fluorescence lidar. We later also developed kHz methods[13,14]. As opposed to insect sampling with sweep nets and traps (see e.g.[15]) remote sensing has the advantages of being non-intrusive, non-perturbing and with known biases and detection ranges and limits. Further, remotely sensed insects are to some extend classified automatically[16,17], whereas analysis of caught insects is tedious but provide more details[18,19]. Most radar entomology studies have targeted high migrating insects by vertical profiling. The size ratio between a large aircraft and insects is roughly the same at the wavelength ratio between microwaves in radar and infrared light and as opposed to microwaves, laser and optics offer great beam qualities allowing investigations of entomological ecology close over ground or within forest without ground clutter. Lidar and photonics methods also offer assessment of molecular and microstructural information through absorption, fluorescence and depolarization processes. Applications of entomological lidar includes monitoring abundance and dispersal of agricultural and forestry pest, disease vectors for humans and livestock and not least assessing biodiversity of pollinators. We will here give an overview of the recent progress in the field.

2. Instrumentation

2.1 Passive lidar

As in passive radar[20], insects can be sensed optically using existing radiation sources such as the sun for diurnal species[21], the moon[22] or thermal infrared emission[23] for nocturnal species. Sunlight offer a range of wavelengths from UV to IR and some 1kWm^{-2} of power. We started out developing the remote dark-field method[21] which gives lidar like signals across the spectrum without need of laser development. This method is based on directing a telescope at a remote black cavity and collect the light scattered from airborne insects. We demonstrated powder tagging and dark-field modulation spectroscopy[24] and heading assessment by quadrant detection[13] (corresponding to beam wobbling in radar). The method can also be employed at several spectral bands at kHz rates for determining body and wing melanisation[25,26]. For some time we attempted passive ranging[27] but only recently provided a solution using quadrant detection[28].

2.2 Time-of-Flight entomological lidar

Equivalently to radar, conventional lidar is based on transmission of ns long laser pulses and recording the backscattered intensity with fast detectors and RF electronics as a function of round-trip delay. Applied systems ranges from slow conventional multiband systems[10,29,30] to fast single band systems[8,31].

2.3 Scheimflug lidar

Similarly to bistatic radar, atmospheric Scheimpflug lidars utilise transmitted and receiver separated by a small baseline of roughly a meter[13,32-35]. The Scheimpflug principle allow infinite focal depth with large apertures[14], therefore weak signals from insect scattering can be retrieved at kHz rates. The average emitted power can greatly exceed pulsed lidars despite the much smaller and inexpensive lasers. The systems can efficiently collect high number of observations[32,34] (See. Fig.1). Scheimpflug lidars can be expanded to retrieve several spectral bands[31,36,37] or polarisation modes[33,35]. For example for assessing melanin (See Fig.2). Scheimpflug lidar can also retrieve fluorescence[38] with applications for insect powder tagging[10,24,39], however violet light may affect the insects[40].

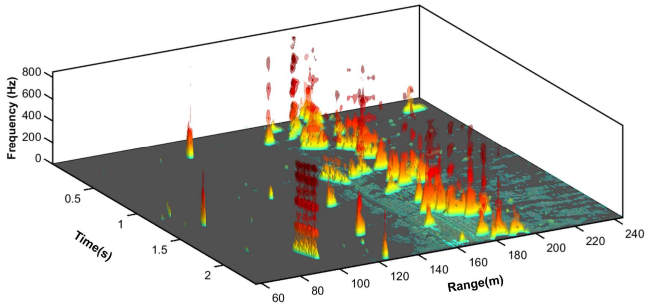

Fig.1. Fraction of entomological data from a Scheimpflug lidar. The lidar was profiling bees over a clover field, the hive was situated 180 m from the lidar. Bees oscillates around 200 Hz indicated by red color code (data from FaunaPhotonics).

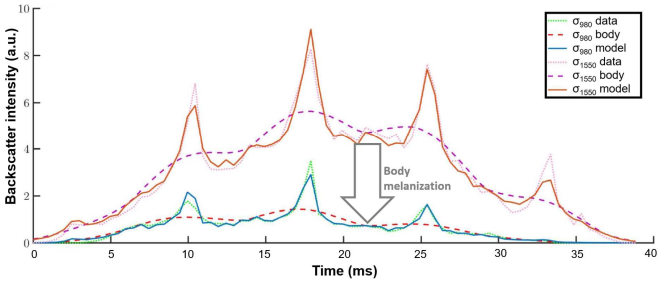

Fig.2. Dual band remote in insect observation using a short-wave infrared Scheimpflug lidar, the melanisation of body and wings can be derived (adapted from[31]).

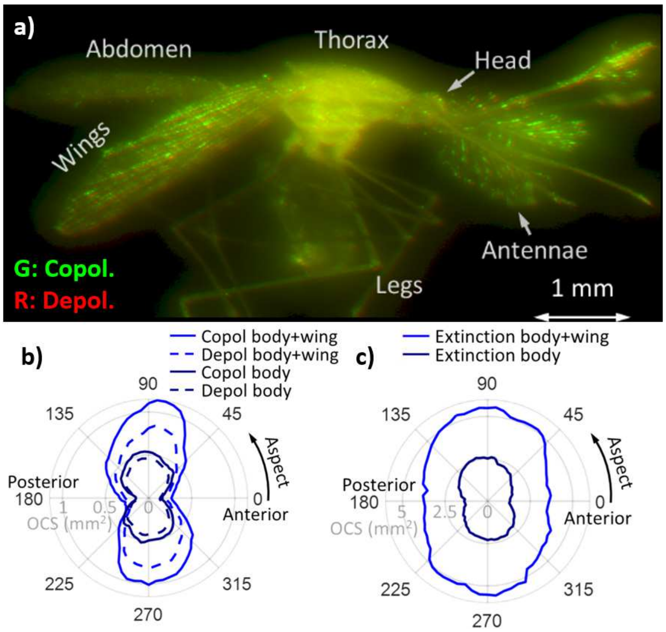

Fig.3. a) Polarimetric image of a dry ♂ *Anopheles* Coluzzii mosquito, 808 nm, 162° backscatter. b) Aspect dependent backscatter cross sections with- and without wings (oscillatory part). c) Corresponding extinction cross section, note the different scale (adapted from[41]).

2.4 Reference measurements

Effort was put into quantifying and understanding optical backscatter- and extinction-cross sections for insects for comparison and feasibility of remote target classification. In analogy with early radar referencing[42] the Montana group recorded polarimetric backscatter of pinned bees[7]. Our group recorded oscillatory cross sections of free flying insects[43,44] including spectral and polarisation modes feasible for lidar. We also applied hyper spectral imaging[45], goniometry[46] and polarisation imaging[41] of pinned insects (See Fig.3). Referencing can also be done by releasing known insects into the lidar beam in field[47] or sampling insect along the beam with a trap[48].

3. Methods, purpose and outcome.

3.1 Organism sizing

If the lidar beam-FoV overlap function can be determined, e.g., by a molecular Rayleigh echo and assumptions of homogeneous atmosphere[32], then backscatter intensities can be converted into Lidar Cross Sections in mm². Whereas RCS related to liquid water mass, Lidar Cross Section was defined as the projected area had the target been a 100% Lambertian reflector such as a Teflon beat. In practice insect reflectance in near infrared[34,41], 808 nm, is in the order of 20%, the reflectance in short wave infrared[45], 1320 nm, is in the order of 80% whereas specular reflectance[46] could reach 5000%. Despite this, organism sizing allow estimation of the aerofauna biomass spectrum[32] and insect and predating vertebrate can display a bimodal biomass spectrum[34]. Biomass spectra are popular in marine science,

3.2 Modulation spectroscopy for target classification

The wing beat cycle causes backscatter and extinction cross section to oscillate with a fundamental tone and a harmonic spectrum. This spectrum has proven valuable for target classification[16,49,50] or even biodiversity assessment[51]. The methods are directly applicable for entomological lidar applications but the work is mainly based on so called E-traps somewhat simpler than lidar and often operating in extinction mode. The drawback is that the counts per day are much lower than lidar[32,34,50]. Much of this work involve advanced machine learning but even the fundamental tone can differentiate species, e.g.[52]. Some challenges are that the tone is temperature dependent[53], that harmonic spectrum is aspect dependent[28,43,44] and that identification of the fundamental tone is difficult[54]. Modulation spectroscopy can be expanded by additional spectral and polarisation bands (See Fig.4).

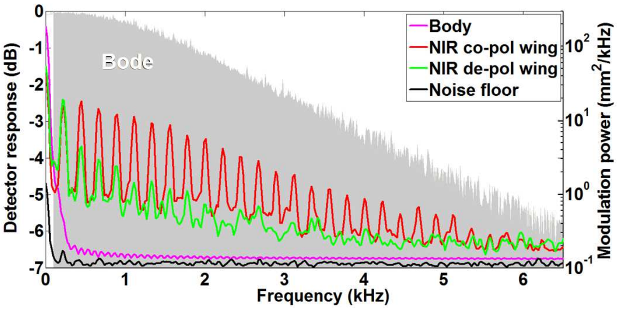

Fig.4. Frequency components of co- and de-polarised backscatter from a *Drosophila Melanogaster* at 808 nm. The high harmonics are from glossy wings and therefore co-polarised (for instrument details see[44]).

3.3 Powder tagging

Insect can be tagged optically using fluorescent powders from the printing and advertising community, and several colours can be used simultaneously. This is referred to as mark-without-recapture studies and yield the greatest certainty about target identity. Social insects such as bees can be auto-tagged by installing a tray in the hive exit. Powdered individuals can be detected remotely either by sunlight[24] or violet lasers[10,29,38]. Applications of tagging include landscape dispersal studies, population size estimates and verifications of classification, e.g., by modulation spectroscopy. Corresponding tagging in radar entomology is accomplished by harmonic radar by attaching electrical diodes to the insects[55].

3.4 Heading assessment

Heading assessment is important for understanding dispersal and migration properties, not least from epidemiological aspects of economic and medical entomology. It can be accomplished in radar by polarisation anisotropy[56], beam wobbling or tracking[57]. In optics heading can be assessed by quadrant detectors[13,26,58], heading could also be inferred by transit times[33] or even and odd harmonics[43] however specular contributions from wings deviates from this model[28].

3.5 Tracking individuals

Reported entomological lidar studies typically report single timings and positions of many individuals, whereas tracking approaches report many timings and positions of a single individual. Tracking radar ornithology is widespread[57] whereas report from radar entomology are limited[55]. In optics efficient tracking can be accomplished by static passive systems[23,59], although active lock-in servo systems have been reported[60].

4. Doppler assessment of movements

Movements of animals and their bodypart may yield small shift in backscatter photon energy, this have been demonstrated with weather radars[61] and micro Doppler radar technology[62]. The reports on applications of widespread Doppler lidars are limited[63].

4. Conclusion, challenges and outlook

We have revised the development of entomological lidar instrumentation and compared it to radar. We have demonstrated aspects of modulation signatures, dual band and polarimetric insect scattering. We have discussed various types of studies and outcome. A current challenge is that there are no table values for scatter cross sections of the millions of insect species. Entomological lidar scientists should be encouraged to calibrate and standardize cross sections for comparison and not report arbitrary units. Future work could benefit from improved reference measurement, and linking lidar recording both to modulation spectroscopy[50] and museum 3D insect libraries[64].

5. Acknowledgements

We thank Mariam Andersson, Peggy Atkinson, Klas Rydhmer, Alfred Strand, Birte Boelt for contributed material. Entomological lidar has been supported by amound others: Swedish Research Council, Norsk Elektro Optikk, FaunaPhotonics, Lund University, Stellenbosch University, South China Normal University, Physiographic Society in Lund, Linnaeus grant to Lund Laser Centre and Center for Animal Movement Research.

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