Photonic Monitoring of Atmospheric and Aquatic Fauna

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Flying insects are of utmost importance in ecology and for human living conditions. Certain species serve as indispensable pollinators to ensure the availability of food stuffs, while others are dangerous vectors for spreading deadly diseases, such as malaria. Agricultural pests reduce the yield of crops, and their abatement through pesticides cause many additional problems. Birds and bats are frequently carriers of diseases, which, especially for long-distance migrants, cause serious consequences. Clearly, there is high motivation to be able to effectively identify and quantify flying fauna. Here, the emerging field of optics and laser-based monitoring of flying fauna is reviewed with an emphasis on remote sensing based on pulsed and continuous wave (CW) lidar systems, and how they complement existing radar techniques. Furthermore, ground-truth laboratory studies are covered. Wing-beat and overtone spectra as well as reflectance, depolarization and fluorescence properties are studied. The aquatic environment is for many reasons less accessible for optical studies, but is clearly also of great importance. Phytoplankton constitute the start of the aquatic food chain, followed by zooplankton and a long chain of higher animals, including fish, an important part of the human food supply. Finally, how optical monitoring can complement sonar and sampling techniques is discussed.

1. Introduction

While man inhabits the land masses of earth, and shares them with a rich fauna variety, the atmosphere and the oceans are in contrast more inaccessible to humans, but well suited for organisms of all kinds with only sporadic intrusions by humans enabled by technology. The monitoring of the atmospheric and aquatic fauna is important for many reasons. Apart from our general quest for knowledge of our environment, there are many practical reasons for a reliable assessment of conditions. The migration of birds has fascinated people for a long time, and besides normal visual ornithological observations, including moon transect monitoring,[1,2] ring and transducer mounting on trapped specimen[3] and ornithological radar techniques formulations are a dangerous trend.[11] Finally, agricultural pest insects[12] consume large portions of crops[13] and again the problem is mostly pertinent in the poorest regions.[14] Agricultural pest abatement is pursued mostly through the strongly expanding use of pesticides, which in turn may put human health in jeopardy because of unwanted side effects.[15,16] Further, pesticides also constitute a huge threat to the pollinators.[17] Again, the development of resistance to pesticides because of overuse is a serious problem. A recent example is the outbreak of massive invasions of army worm in southern Africa,[18] believed to be caused by pesticide-resistant specimen, which were accidentally brought in from South America. For these, and additional reasons, effective monitoring of the locations and action of flying insects is of considerable interest. Apart from sampling techniques

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traditionally pursued by entomologist, short-wavelength radar systems have proven effective in long-range monitoring of flying insects. However, such systems cannot record close to the ground and yield limited specificity.

The areas of water bodies dominate over land on our planet, and small organisms—phyto- and zooplankton—form the basis of the aquatic food chain. Aquatic ecosystems can exhibit considerable vertical structures with regard to temperature and salinity, and the abundance of organisms shows rapid changes such as the daily vertical displacement of zooplankton. Conventional methods with nets and water sampling are widely used followed by detailed analysis including microscopy. Echo-sounding devices (sonars) are also widely employed. Acoustic sounders have considerable range of hundreds of meters and are capable of detecting fish and fish shoals, and to a certain extent also observing plankton layer structures. Aquaculture and salmon farming has evolved to large-scale production, constituting a significant nutrient resource, in particular emerging from the fjords of Norway and Chile. As a consequence of the densely caged salmon population, salmon lice have emerged as a significant challenge. Monitoring systems with specificity between parasites and prey are much desired. Several initiatives for monitoring aquatic microorganisms are under development.

Air- and space-borne passive sensors operating in different frequency bands, have been developed for large-scale mapping of the vegetation, water bodies and atmosphere. Whereas these methods provide global or large coverage, depth profiling is absent or very coarse, and tempo-spatial resolution is low with shortest sample intervals of half a week if cloud cover allows, and is often limited to the same hour of the day. Active light detection and ranging (lidar) methods for vegetation, water, and atmosphere, can yield higher resolution and depth profiling but less coverage. Complementary passive and active methods provide particularly valuable access to the oceans and the atmosphere, which are less readily accessible than the terrestrial features. While extremely successful in mapping earth resources, water bodies especially with regard to algal blooms, and atmospheric conditions, which all are also related to the ongoing global change due to human activities, the existing disciplines provide little direct information on atmospheric and aquatic fauna. There is certainly room for the development of new and powerful tools to provide such information, which is presently only scarcely available.

The present review deals with advanced photonics approaches to observe atmospheric and aquatic fauna. We will focus on remote-sensing methodology, since the subject matter strongly relates to assess fauna, which by nature is normally outside immediate reach of the investigator. Lidar approaches then present themselves as very valid possibilities. The area is quite new and now strongly developing.

The structure of the paper is as outlined below. We describe basic interactions and measurement principles relevant to the topic in the following section. Basic properties of the ambient media, that is, atmospheric air and water, respectively, are then presented, since especially the spectral transmission of electromagnetic radiation is highly relevant. We will then cover some relevant laboratory studies, which exhibit phenomena, which are useful also for remote sensing of atmospheric and aquatic fauna.

We will then review a number of studies, where novel and advanced photonic approaches are used in situ.

Lasers and photonics are well established in environmental monitoring, offering continuous surveillance of the health condition of our surroundings. Satellites provide, mostly with intervals of weeks, global coverage of atmospheric constituents such as particulates and gases even with coarse altitude distributions thanks to techniques such as differential optical spectroscopy (DOAS) and limb probing. Also superficial layers of water bodies can be evaluated from space in terms of chlorophyll and dissolved organic matter (DOM). Smaller environmental devices constitute a commercial market and monitor air and water quality locally at high temporal resolution; see, for example, refs. [42,43]. Such devices alarm the municipality when urban pollution exceeds safety levels, when bacteria are detected in the drinking water, or shut valves in industrial settings when leakages are detected. Most countries with a research budget have one or several investigative teams developing optical and laser profiling of the atmosphere (see, e.g., refs. [44–47]); in particular atmospheric lidar is widespread. The vast majority of atmospheric lidar activity worldwide treats the topic of aerosols;
natural dusts, volcanic ashes, anthropogenic soot—the continental transport and the impact on the global radiation budget—while fewer deal with the differential absorption lidar (DIAL) for gaseous pollutant monitoring.

Complex systems such as atmospheric lidars are primarily employed for fundamental scientific understanding of atmospheric mechanisms and provide little direct online value to the citizens; commercial atmospheric lidars constitute a rather small business. Even more realistic environmental sensors for air and water quality, employed by authorities and with direct upload to meteorological portals form a niche market compared to environmental sensors in industrial setting. Why is this so? Before speculating on the reason we will give another example.

In recent decades small compact airborne- or vehicle-based topographic lidars have emerged commercially. A subbranch, namely profiling vegetation structures, has in the past years experienced an explosion of studies. The method provides a quantitative description of the height distribution of vegetation structure over ground. Despite the fact that plant species classification is still limited, the research topic is flourishing with studies ranging from correlating vegetation with preferred habitats of animal species or evaluating the defoliation from pest attacks on forestry. No wonder these methods retrieved attention from forestry and agricultural industry, and vegetation lidars now find their way into commercial solutions in smart agriculture or timber yield assessment.

One explanation can be found when comparing a diagnostic tool in environmental monitoring to the available counter measures; if the environment is exceedingly polluted, then the societal costs are indirect, the cost are increased sick days and days of hospitalization, which may or may not be at private or state expense. Counter-measures are often through slow changes of legislation and regulation by authorities. In the worst cases, pollution sources are beyond the borders of a nation and the only treatment option is tedious international agreements. With the egocentric economic structure promoted in modern times and the largely prevailing paradigm that environmental sustainability is opposed to economic growth, this international debate often runs into difficulties, where the fate of the global ecosystem relies on the irrational cooperative human nature.

In the case of vegetation lidar utilization, players in forestry and agriculture have a direct economic interest and motivation for investing in laser photonics diagnostic tools. It is crucial to evaluate yield, and to rapidly identify pest outbreaks. Pesticides are not only means to avoid the risk of losses, they also constitute an expense and they may reduce the value of the crops given an increasing ecological awareness.

Our hope is that such direct benefit can motivate the development of optical monitors for entomology and consequently result in quantitative diagnostic tools, which are directly needed in the argumentation of managing authorities for conserving fragile ecosystems against unsustainable industry.

The animal kingdom extends from the North pole to the South pole and organisms can be encountered in the height and depth span beyond $+/-10$ km from the sea level. As can be understood, optical environmental monitoring has primarily targeted the smallest and most abundant atmospheric constituents, namely atoms, molecules, and aerosols. Whereas table values exist for absorption and scatter cross sections for molecular species, and whereas numerous groups have developed scattering theory for distinct aerosol classes, the millions of living species present in the atmosphere and the water masses here lack both table values and basic scattering models. This immense challenge could discourage many researchers, but gives more reason to get started.

We review in this work how we could grasp the abundance, dynamics, and also distributions of the living organisms on our planets with direct detection employing laser photonics. What has been done? What are the challenges? What are the opportunities? We limit ourselves to the animal kingdom, since laser photonics for vegetation is a discipline of its own. Similarly, we will not go into depth regarding animal coloration. We exclude the topic of photonic surveillance of humans, because this tends to be a military topic with a doubtful logical chain of arguments regarding the political discussion on which civilization should possess the most sophisticated technology. We will not cover light interaction with human tissue which is treated saliently in the literature on biomedical optics; see, for example, ref. [58]. Our topic bridges the topics of remote sensing and biophotonics.

2. Detection and Light Interactions with Aquatic- and Aerofauna

2.1. Sparseness, Focusing, and Detection of Fauna

Before addressing the issue of how light interacts with aquatic- and airborne fauna we must understand some of the essential aspects of fauna constituents in our environment which differ from conventionally studied substances such as bulk atmospheric or aquatic media, pollutants, particulates, or trace gases. The spatio-temporal structure of fauna is sparse. This implies that the likelihood of observing an organism in the probed volume is much smaller than observing the bulk medium (air or water). However, the contrast between bulk media and the organism is generally very high if an appropriate optical detection scheme is implemented. Calculating the statistical distribution of the signal from a given optical system, monitoring the environment will produce a Gaussian distribution with an offset from the bulk medium signal and a width according to the noise of the system. Rare events from living organisms will produce a small symmetric shoulder on the distribution, increasing the statistical skewness (see Figure 1). This detail is often only observable on logarithmic scales and the significance heavily depends on system sensitivity, spatial resolution (the point spread function (PSF) rather than the number of pixels/voxels) and temporal resolution (bandwidth rather than sampling rate).

The sparseness of fauna poses a fundamental challenge in optics: organisms appear and disappear rapidly at random positions in space. To achieve high sensitivity in optics we need focusing, but without knowing where to focus in advance this poses a challenge. Large focal depth can be achieved by pinhole cameras, but this ruins both sensitivity and temporal bandwidth.

One can take inspiration from other sparse samples such as in nephelometry or cytometry. This essentially implies reducing the probe volume to a single point, which can then be adequately focused on and illuminated. The sample is then
pushed through this point by a nozzle with flowing air or liquid while particles are counted and classified. Although not directly compatible with living animals such approaches can and have been pursued\cite{28,65–67} If the method relies on larger organisms to intercept the probe volume unperturbed by any attraction means, the reported counts and efficiency for gathering data are rather low,\cite{68} and such approaches seem most efficient when combining laser sheets\cite{69} with organisms in the smaller end of the biomass spectrum.\cite{70}

Another approach for focusing on sparse particles is post-focusing with digital holography.\cite{71} Post-focussing techniques are known from phase arrays in acoustics\cite{72} and radars\cite{73} and also from radio astronomy, although this has so far not been applied to aerofauna.\cite{73} In optics, this detection scheme consists of an imaging transmission measurement where a narrow-band laser is expanded for probing a large volume, and then projected on a CCD or CMOS array. The sensed property in digital holography is based on extinction and refractive index. Extracted features include projected shapes\cite{74} and heading trajectories.\cite{75} The method has primarily been successfully applied to microscopic aquatic organisms such as diatoms. To date, digital holography is the leading optical, automated, in situ monitor in terms of specificity.

Inspiration from nephelometry and cytometry regarding reducing the probe volume to a point has been applied in aquatic environments, for example, ref.\cite{76}, and because of the large abundance of microorganisms this can be valuable. Similar to nephelometry and cytometry, the parameter space can be increased by adding additional scatter angles,\cite{65} polarization,\cite{63} and spectral bands.\cite{78} A number of point monitors for aerofauna are in development.\cite{58,79,80} In terms of optics, the projects are simple featuring a single kHz transmission measurement with a single spectral and polarization band. The reported observation number from these devices are disappointingly low, but numbers could possibly improve in combination with bait or light attraction.

Appropriate focusing on sparse organisms is not only a prerequisite for efficient recording of large observation numbers and gaining the necessary sensitivity for detection. Focusing, and in particular ranging, play a crucial role in calibrating scatter cross sections to absolute values. Similarly to the wavelength efficiency curve of spectrometers, instrumentation for scattering, such as lidar systems, have a range-dependent sensitivity referred to as the form factor.\cite{81} For a homogeneous atmosphere or aquasphere, the form factor can be observed as a distributed echo given that the lidar has the necessary sensitivity. The resulting signal from an animal is a function of the spatial product of the illuminating beam, the field of view (these two constituting the probe volume), and the organisms transiting the probe volume. In good situations where a form factor is available, an intensity signal can then be converted to a scatter cross section corresponding to square millimeters—if the target had been entirely Lambertian and white. In cases where the optical extinction is recorded, the extinction cross section corresponds to the projected area of the organism for the case when the target is entirely opaque to ballistic light. In cases where both backscatter and extinction are retrieved, the absolute reflectance can be derived. Absolute optical cross sections have important applications for animal sizing and acquiring the biomass spectrum, and serve as a basic parameter for qualified guesses on species groups.

2.2. Angular Domain

Detection of sparse aero- and aquatic fauna is possible in several angular configurations. The angular domain refers to the angle between light propagation before and after sample interaction. The lidar principle\cite{34} operates in backscatter mode detecting light which has scattered $180^\circ$. Methods such as lunar obscuration,\cite{2} digital in-line holography\cite{71,82,83} and various entomological modulation spectroscopy devices\cite{67,79,80} operate in transmission mode close to $0^\circ$ in the angular domain. Passive dark-field methods\cite{61,84–88} based on sunlight, where the field-of-view is terminated in a black cavity, operate at angles between $180^\circ$ and $90^\circ$. In most situations regarding sparse organism detection, organisms would only account for a fraction of the

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**Figure 1.** a) Backscattering values retrieved for clear air using a lidar system. Seldom, the backscatter is hundreds of times compared to the value for the bulk medium. The observation is attributed to sparse particulates including aerofauna. Reproduced with permission.\cite{59} Copyright 2010, SPIE. b) A simplistic paradigm of the size-dependent abundance of atmospheric constituents, along with employed surveillance technologies and their operating wavelengths.
probe volume in efficient detection schemes capable of detecting large numbers. Many insects are small compared to the mean free scatter path length. Therefore, forward scattering can greatly exceed backward scatter for small organisms.\cite{89}

As opposed to transmission measurements, side- and backscattering belong to the zero-background category. Although organisms are few and sparse, the contrast between scattering from biological tissue and that of ambient media such as clear air or water is very large. Generally, there is a massive advantage of detecting different scattering from 0.1% to 1% as opposed to detecting an extinction from 99.9% down to 99%. In point monitors and laboratory setups, multiple angular modes of side scatter and extinction can easily be added.\cite{90,91}

In lidar, extinction can be estimated by the reduction in the post-echo compared to the static value.\cite{92,93} A reliable extinction assessment in lidar enables absolute reflectance measurements.

Apart from the angle between light propagation prior and after sample interaction, scattering from living organisms is highly anisotropic\cite{89,95} and the scatter cross section depends on the observation aspect such as pitch, roll, and yaw.\cite{89,96,97} see Figure 2a,b. Turntables and computerized tomographic algorithm allow 3D reconstruction of, for example, insects.\cite{98} Despite that a number of symmetry constraint can be imposed which reduce the shapes that the scattering lobes can exhibit,\cite{99} the interpretation of fauna scatter from arbitrary aspect is challenging. Zenith or nadir observations greatly simplify this matter.\cite{88} This is because lateral transport dominates over vertical transport and the anatomical axes are predominantly horizontal such that optical cross sections remain invariant with heading angle. Also certain band ratios such as depolarization or melanization have been shown to be largely angular insensitive.\cite{91} The increased scatter from ventral observations can also be exploited to derive body orientation.\cite{100} Specular wing reflectance is coherent and displays tight relation of illumination and observation angles; see Figure 2c,d. Such membranes can be investigated in the laboratory, for example, by spectral goniometric ellipsometry.\cite{57,94}

2.3. Frequency Modulation Domain

The number one domain to consider when detecting aero- and aquatic fauna is the one of frequency modulation.\cite{79,101} A
common feature to any animal occupying the airspace or aquasphere, is that it needs to ensure levitation, propulsion, or filtering oxygen or nutrients. Hence, any kind of optical cross section, being backscatter, extinction, or fluorescence oscillates! Apart from the sparseness, this is a truly unique feature of all fauna detection. In Figure 3 interpretation details are plotted against frequency content. Conventional atmospheric lidar is indicated in the top of the figure. This implies that any sampling system with insufficient temporal bandwidth or sampling frequency would sample the animals in a random phase in their oscillation. Whereas birds and bats have wing-beat frequencies in the 1–100 Hz range, insects oscillate at 10–1000 Hz. The literature on oscillation of aquatic organism is very limited but values above 100 Hz have been reported.\[90\]. The frequencies are somewhat characteristic to the species, perhaps more in entomology than in ornithology. In particular, sexes are known to differ considerably, for example, for mosquitoes.\[91,101,104\]. However, the fundamental frequency is temperature dependent,\[105\] and temperature coefficients are different for different species. On top of the fundamental frequency, the cross section of organisms has a waveform corresponding to a harmonic series. The waveform or harmonic spectrum summarizes the geometrical projection of the animal as well as the dynamics of the wings of the aerofauna.\[99\]. The modulation spectra have been demonstrated to distinguish species, even closely related, by several independent research groups.\[84,79\]. The harmonic spectrum for an individual depends on the aspect of observation,\[99\] and vertical probing greatly cancels out these geometrical challenges.\[24,106\]. The modulation content can also differ between spectral bands because of different pigmentation on different body parts.\[85,86,91\]. The flat and sometimes glossy wing membranes of insects can produce specular spikes on the wing-beat waveform. The specular spikes can be recognized by polarimetric modulation spectroscopy\[91\] and we have observed up to the 28th harmonic,\[94\] and then still limited by instrument bandwidth. Therefore, the inherent frequency content of insect wing beating may easily exceed 30 kHz. Glossy wings can for some species be associated with age groups.\[107,108\]

2.4. Polarization Domain

Although passive polarimetry is possible,\[109\] the primarily investigated area of polarimetric application is for distinguishing co- and depolarized backscatter in active sensing techniques.\[91,97,110,111\]. Essentially, singly scattered photons from glossy target surfaces and photons due to Rayleigh scattering from the molecules in the bulk, surrounding medium is entirely co-polarized. Photons which have undergone multiple scattering and photo-migration in biological tissue,\[95,112–114\] body fur or plumage of diffuse microstructure could display large degrees of depolarization. Thus, the depolarization ratio (degree of linear polarization, DoLP) reports on the target glossiness. Absorbing pigments such as melanin mainly apply to the depolarized parts, which have entered the biological tissue and undergone a migratory path subject to absorption due to the Beer–Lambert law. Therefore, even melanized targets can be expected to display less depolarization and higher DoLP. However, there are cases of nanostructures reducing the surface reflectance below predictions by the Fresnel equations.\[115–117\]. Similarly, there are reports of extreme scattering coefficients for producing white reflectance in thin cuticles.\[118\]

Figure 3. Optical signature of insect lidar targets decomposed into increasing details of interpretation toward the right. The percentages indicate rough magnitudes of contributions, the frequency content increases toward the bottom of the chart. Conventional atmospheric constituents for lidar studies are indicated at low frequencies at the top.
Several studies have been conducted in the radar microwave regime using decommissioned missile tracking systems.[5] These systems include beam wobbling which also spins the polarization. Because radar cross sections (RCSs) arise from the water content in the body and since bodies are elongated, the body orientation can be inferred in radar entomology and ornithology.[119]

Given that a method is capable of resolving co- and depolarization as a function of wing-beat phase, see example in Figure 4,[91,120] information on glossiness and furriness may be inferred both for the wings and the body of the organism. Examples include depolarizing bodies of bees[97] compared to glossy cuticles of ordonates, and matte depolarizing wings of moth and butterflies as opposed to glossy wings of mosquitoes, tapanides, and flies. Birds and bats may be expected to produce depolarized signals. In sensing of aquatic organism the knowledge is somewhat limited regarding depolarization.[121]

2.5. Spectral Domain

Animal coloration is a very extensive topic,[56] which has been pursued for a long time,[122] and we can only briefly touch on the topic from a sensing perspective in this work. Very exotic photonic manipulation can be found in insects,[123] birds,[124] and aquatic species.[125,126] However, the larger fraction of species are less spectacular, and for the purpose of sensing and target classification we will focus on the generally applicable features across species.

2.5.1. Deep UV

The deep UV region (200–300 nm) has been explored only little for animal sensing.[110] The region is challenging in terms of standard optical components, and laser sources are currently costly (eximer and frequency-quadrupled Nd:YAG lasers at 224, 248, 266, and 308). Future doubling of high-power blue laser diodes may overcome this situation.[127] The region in itself is interesting since air is transparent but optical background radiation is absent due to the ozone layer around 30 km in altitude, and defeating optical background is a prime challenge in atmospheric lidar. Both keratin[128] and chitin[129] exhibit peak absorption around 280 nm. Consequently, this deep UV radiation efficiently induces violet fluorescence[130] in these bulk polymers encountered in the epidermis across the animal kingdom. See example in Figure 5. This leaves some opportunity for

Figure 4. a) Co- and depolarized backscatter over time from a fruit fly recorded in the laboratory. Co- and depolarized contribution from the body is estimated from a sliding minimum. Note that spikes are absent in the depolarized channel. b) Frequency content of the same data illustrate how specular spikes induce high harmonics. The $-3\text{dB}$ bandwidth of the detector is shown.[91,94]

Figure 5. Excitation–emission fluorescence spectroscopy of a biting midge in the deep UV. The color coding is logarithmic. Possible fluorophores could include tryptophan, pyridoxine, tyrosine,[132] and chitin.[130] Data kindly provided by Carsten Kirkeby.
Figure 6. Recapitulation of the rich optical phenomena and visible light manipulation in the animal kingdom: 1) polarization optics with liquid crystals, 2) patchiness, 3) thin film effects, 4) iridescence, 5) tissue optics, 6) cryptic transparency, 7) thermal vision, 8) bioluminescence, 9) video reproduction, 10) absorption, 11) non-iridescent structural colors, 12) long pass filtering, 13) nanophotonics, 14) circular dichroism, 15) chromatic light modulation, 16) metallic reflectance, and 17) fluorescence marks, where particular references can be found.

spectral analysis and classification even within the dark spectral region below 310 nm. Melanin fluorescence can be observed but the main influence is quenching of excitation and emission light. Several fluorescence lidar systems were developed in the deep UV for the purpose of distinguishing natural bio aerosols, such as pollen, from biological warfare agents. Differential absorption and depolarization may also be pursued in the deep UV range. An important aspect when considering monitoring animals through absorption of pulsed or modulated lasers is the induced photoacoustics. Most animals have supreme sense of sound and vibrations and are likely to be perturbed by induced vibrations in the kHz range despite that light may be invisible.

2.5.2. UV–Green

In the UV–Green region (330–550 nm), the majority of animal vision systems is polychromatic and extending over human vision in bands and UV coverage. For this reason animal coloration is also rich in spectral manipulation in this range; see, for example, ref. [135] and Figure 6. Frequently encountered pigments are carotenoids but in particular spectral features are produced by organized biological tissue (photonic crystals). Frequently encountered components are keratin/chitin (1.55), air (n = 1), and melanin (1.75) and the spherical symmetry of spatial frequencies determines behavior such as iridescence or glossiness. Since animal would react to light in this range, it is challenging to monitor animal unperturbed in this region. Either one must consider this perturbation and sample with snapshot or sample sequences, and estimate the perturbation. Another approach is to induce broad-band fluorescence in the tissue with invisible light in the deep UV region. The broad-band light will in turn be imprinted by both structural features and pigments in the visible region.

Aquatic lidar operation is constrained to the UV–visible region due to liquid water bulk absorption. Most work on aquatic lidar has been performed with green doubled and UV tripled Nd:YAG at 355 and 532 nm. Work includes elastic backscatter, polarimetric backscatter, and fluorescence lidar. Recent development of high-power (1–30 W) GaN lasers in the violet (405 nm) and blue (445 nm) regions can greatly reduce size and complexity of future aquatic lidar systems, and a number of aquatic applications of these laser diodes can be expected as their emission coincides with reasonably low absorption of water.

2.5.3. NIR

The near infrared (NIR) region (700–1000 nm) is attractive from many aspects: The light is almost invisible to animal vision...
Erbium fiber lasers as well as diode lasers, not the least at the telecom band at 1550 nm. For detection, InGaAs sensors are available as quadrants, avalanche photo diodes (APDs) and 1D and 2D arrays for a prize ten times that of Si detectors, but still available off-the-shelf. A peculiar feature of aerofauna in the SWIR region is that melanin absorption is absent, and thus birds and insects can be assumed white at 1064–1320 nm. This allows assessment of the absolute cross section without interference from reflectance. It also allows quantification of melanization through differential absorption. For insects, SWIR bands in the 1470–1550 nm range can be expected to be absorbed by liquid water in the abdomen tissue. This biophotonic interaction could be exploited in several ways, for example, for assessment of scatter coefficients. A significant advantage is that eye-safe bands can be selected from 1.4 μm and upward.

2.5.6. MIR/TIR

The mid- and thermal-infrared regions (MIR 3–5 μm resp. TIR or LWIR 8–12 μm) are commonly used in military optics and could enable interesting research in ecological studies not the least in ornithology of night migrating birds. A number of ecological applications have been reviewed. Detection involves InSb and HgCdTe technology associated with Sterling coolers, vacuum, and cold shields. The devices are often subject to export restrictions and photonic development requires substantial resources. MIR light sources such as quantum cascade lasers (QCLs) can be expected to be more widespread in the future. In the thermal IR (TIR), high-power (W-kW) CO₂ gas lasers can be acquired at 10.6 μm for decent costs. In the middle IR (MIR), several absorption features from waxes and lipids can be encountered; these have been demonstrated for classification of species and age groups in FTIR studies. The periodicity of the ordered microstructure of plumage has been demonstrated to resonate and produce iridescent features in the MIR, essentially for any species. Another interesting phenomenon is the Christiansen effect, where Mie scattering disappears (see Figure 8). For keratin and chitin this occur at 6 μm, where the atmosphere is opaque. Thermal radiation transfer in plumage is additionally investigated in metabolic research.

2.6. Coherence Domain

We already covered coherent methods such as holography and we elaborated on the coherent nature of specular spikes and thin-film effects in the spectral interaction. What remains to be discussed is the Doppler instrumentation on the borderline between elastic and inelastic methods. The photon energy shifts marginally when backscattering from a moving target (see Figure 9). The conventional way to detect this shift is by interferometry, thus letting the backscattered signal interfere with a reference wave with very long coherence length (narrow spectral width). The tiny spread of photon energy can also be directly evaluated. This challenging discipline is referred to as high-spectral-resolution-lidar (HSRL). When considering
entomological and ornithological targets, both the individual as a whole and the body parts certainly move. This property is exploited in Doppler radar where animal targets can be contrasted against ground clutter over far distances.[21,166–169] Coherent Doppler lidar methods engage a significant community, despite that sampling rates are in the MHz range and the effective temporal resolution after Fourier windowing and averaging is much lower. So far aero- or aquatic fauna have only been investigated by Doppler means on a population level[170] and not on the individual level.

2.7. Inelastic Monitoring Methods

Inelastic scattering such as fluorescence and Raman scattering from aero- and aquatic fauna are the weakest interaction mechanisms. Overcoming optical background is a severe challenge, and most inelastic detection methods are mainly limited to nighttime operation or deep sea applications. The bulk material in bird plumage and bat fur is keratin, whereas the cuticle of insects and aquatic fauna, such as crustaceans and copepods, is made from chitin. Spectroscopically, both keratin and chitin are similar and essentially transparent down to 330 nm. In both cases absorption peaks occur around 280 nm. Therefore, the popular lidar band of 355 nm is of little efficiency for inducing fluorescence, and choices should focus on more challenging lasers at 248, 266, and 308 nm. Melanized plumage, fur, and chitin cuticles effectively absorb excitation light and quench fluorescence from 300–1000 nm. There are few exotic prominent fluorophores reported in birds.[124] The majority of spectral signatures in the UV–green region are caused by carotenoid chromophores or are of structural origin generated by organization refractive indices of chitin/keratin, air-, and melanin inclusions,[16,139] as such there is little basis for fluorescence except from that of chitin/keratin. In cases where fluorescence is efficiently induced in chitin/keratin, the emitted radiation is heavily imprinted both by structural features and pigments in the UV to green region.[110] Fluorescence can exhibit characteristic lifetimes in picoseconds, to our knowledge this is challenging to exploit in stand-off detection but some decay times for fluorophores are listed in biomedical optics.[172]

Many of the smaller aquatic organisms are highly transparent except for the eyes and intestines. One of the most prominent fluorophores of these organism is chlorophyll in the consumed phytoplankton.[173] The majority[174] of aquatic species are renowned for bioluminescence and a number of inherent fluorophores,[54] for example, the green fluorescent protein (GFP)[175] can be encountered. In deep environments, fluorescence could find application with larger success, not the least considering the absence of optical background. Despite bioluminescence controlled by the will of the organisms, laser activation cannot be excluded.[176] Both corals[177,178] and coral reef fish[179] can exhibit auto-fluorescence features which have been exploited to monitor the health of these endangered habitats.

As opposed to auto-fluorescence, tagging with fluorescent dyes can yield much stronger signals. The equivalence in entomological radar is electrical diode tagging and harmonic radar.[180–182] Ornithology studies are carried out by ring marking and tagging with GPS, sunloggers, and accelerometers, and aquatic studies include RFID tagging and well as GPS on larger species.[3]

The advantage of fluorescence tagging[183] is that it yields a great certainty about the identity of the detected individuals. Fluorescent powders are available as toners from advertising industry and stick to insects by electro-static forces similarly to pollen. Powdered individuals can remain tagged for several weeks, and be detected both by fluorescence[60,184] and elastic scattering.[84] Several groups of organisms can be tagged by distinguishable powders for comparative studies.[184] The drawback is that organisms need to be captured for tagging. However, organisms such as social insects, can be auto-tagged, for example, by a powder tray at the hive exit and in this way ensure
...that detected organisms pertain to a certain colony. Powder tagging\textsuperscript{183} may also be used for estimating populations.\textsuperscript{185}

Overall, there are rather few operational fluorescent lidars engaged in biological targets. In the beginning of the millennium, NATO sponsored a number of inelastic lidar development projects for detection and characterizing of biological aerosols such as pollen and bio warfare agents. The instrumentation and feasibility is discussed in ref. [45]. Historically, fluorescence lidar research has also been pursued particularly in Italy\textsuperscript{186–188} and Sweden.\textsuperscript{184,189–192} More recently, CW fluorescence lidar systems have been developed.\textsuperscript{193,194}

Raman signal detection in remote sensing and stand-off applications is exceedingly challenging. However, Raman signals from the surrounding, bulk media such as N\textsubscript{2} and liquid H\textsubscript{2}O, are popular to calibrate lidar measurements and to derive range-resolved extinction coefficients.\textsuperscript{92,93,195} Apart from calibrating scatter cross sections, bulk media Raman signals may report on temperature and salinity.\textsuperscript{196,197} In the context of detecting sparse organisms, extinction may equally well be estimated by comparing elastic post-lidar echoes to the static signal echo from the bulk medium.

2.8. Thermal Methods

While the atmosphere has several transmission windows for thermal radiation, the aquasphere remains entirely opaque for infrared radiation. None-the-less, warm-blooded marine mammals such as whales\textsuperscript{193} and seals\textsuperscript{199,200} (pinnipids) can yield high contrast in the infrared region against the cold environments when breathing near the surface or resting on sea ice. The combination of surface temperature gradients with the vortex wakes from whale flukes can produce thermal traces on the sea surface with periodical structures in both space and time.\textsuperscript{201} Such features could possibly shed light on the target identity. Turning to applications to aero- and terrestrial fauna,\textsuperscript{202,203} so far thermal monitoring has been applied in ornithology.\textsuperscript{204,205} Although sophisticated infrared-search-and-track (IRST) systems\textsuperscript{206,207} and multispectral and polarimetric\textsuperscript{208} thermal cameras have been developed, most existing studies are carried out with a single spectral band leaving room for interesting but challenging photonics research. At zenith observation against the black clear sky, birds yield fairly large contrast, not because of plume temperature, but because of the high emissivity compared to air in the atmospheric windows. Night migrating birds and bats can be observed with thermal imaging\textsuperscript{23} including stereo vision (see Figure 10).\textsuperscript{209} The main obstacle for improving specificity is that these least costly devices do not possess the temporal bandwidth for resolving wing beats and harmonics. Direct bandgap detection with InSb or HgCdTe sensors is capable of resolving fast phenomena but require deep cooling with liquid nitrogen or Sterling pumps, which are subject to export constraints. Also, InSb and HgCdTe arrays are normally outside the budget for ornithological studies. Despite the difficulties, the spectral emissivity from the organized structure of plumeag can be expected to have a large number of peculiar features yet to be explored.\textsuperscript{155} However, the high ground speed in combination with low wingbeat frequency of birds imply that telescope tracking is generally required to acquire wing beats and harmonics spectra. Currently, several projects combine radar and infrared imaging in relation to detection of endangered species with reference to the wind power industry.\textsuperscript{210,211} These projects rely on combining several disciplines such as thermal optics, microwave engineering, and automated control into rather complex systems, which may exceed the capacity of individual research groups. Infrared search and track (IRST) systems\textsuperscript{206} are perfectly capable of tracking and extracting several interesting features from night migrating birds. Future decommissioned IRST systems are likely to further advance thermal ornithology. Currently, entomological lock-in and tracking have been demonstrated on laboratory scales\textsuperscript{212} by using galvanometric servo systems and cameras; however, outside the thermal regime.

The spectral, polarization, and angular properties of emissivity and thus thermal radiation are susceptible to ordered surface structures.\textsuperscript{213–215} In the case of feathers this microstructural information may in the future be used to classify thermal targets.\textsuperscript{155}

3. Laboratory Studies and Automated Traps

Conveniently, pilot and feasibility studies in animal sensing can be performed in laboratories. Ethics regarding handling of living vertebrates such as bats and birds constitute a substantial concern, while in vivo studies of insects and aquatic species are straightforward unless the species are endangered, or a pest with...
risk of spreading from the laboratory. Apart from the oscillatory properties, dried ex vivo specimen of birds and insects essentially preserve their optical characteristics across the spectrum.\[^{98,148,217}\]

One exception is the imprint of liquid water absorption in the SWIR region for insects and bats (only a fraction of light would reach biotissue through the plumage). Ex vivo aquatic species are unlikely to produce representative results unless entirely fresh.

Reference measurements in laboratories serve as an important basis for making qualified guesses for remote sensing in situ. Fresh insects have been mounted on thin threads in radio dead chambers for entomological radar studies. The specimen is rotated and the RCS is recoded from all angles.\[^{96,218}\] Similar angular cross-section studies were pursued at 532 nm with a polarimetric setup on bees.\[^{97}\] Here the furry body exhibited a high isotropic depolarization ratio of 20%, whereas the glossy wings had minimal depolarization at specular conditions and a value of 10% when parallel to the beam. The results are consistent with the understanding that furry and diffuse body parts depolarize, and glossy wings produce co-polarized and coherent light when their surface normal coincides with the beam.\[^{99}\] The depolarized light is more affected by absorption; thus the depolarization is generally larger in the NIR and SWIR regions.

Animal coloration, in particular for the more spectacular species, has been extensively investigated. The methods include spectroscopy,\[^{56,57}\] goniometry, ellipsometry,\[^{219}\] hyperspectral imaging,\[^{150}\] polarization imaging,\[^{220}\] and many other techniques. Studying this literature is rewarding for grasping a fraction of the ways that light can interact with animals, and also in relation to the innovative instrumentation which has strived to capture the many aspects. The work mainly covers the visible, but also the ultraviolet region, and may not be directly applicable for remote-sensing purposes in the NIR and SWIR domains. Nevertheless, aspects like melanization may be extrapolated into the infrared with some knowledge in biophotonics.\[^{95}\]

Animal locomotion and biomechanics is a classical topic of investigation. Studies are primarily carried out using multiple high-speed cameras operating in burst modes for capturing specific events.\[^{221}\] Studies include flight mechanics of individual organism as well as interception events between prey and predators. The associated image processing is often massive and includes 3D parametrization of position, velocity, body orientation as well of the surface normal of each wing in every frame. Another popular area is particle induced velocimetry (PIV), targeting the air or water flow around the moving animal.\[^{222}\] These studies are carried out, for example, in wind tunnels with pulsed Nd:YAG lasers and are capable of providing quantitative details on flight efficiency and energy losses.

Laboratory setups for tracking aquatic animals have been carried out on species ranging from submillimeter organisms to larger fish shoals. Tracking of multiple individual copepods was carried out by stereo viewing and tagging with fluorescence quantum dots.\[^{223}\] From this approach, daily depth migration in relation to sunlight was investigated. Similar studies can be carried out with other dyes.\[^{93}\] Recent progress in digital holography has enabled similar tracking of microorganisms, where multiple movement trajectories are recorded, demonstrating alternating propulsion modes. Ensembles of fish have been monitored in shallow laboratory tanks, and astonishing group behavioral properties, similar to those encountered for photons and electrons, have been demonstrated, for example, how group size increase collimation of propagation\[^{224}\] or orbital shell-like structures.\[^{225}\]

Similar laboratory studies have captured predation fields which have a correspondence to reaction chemistry in ecology. The obstacle for pursuing research on similar interaction mechanisms in situ is the need for precise target classification, and mapping out the cross-species interaction strength in situ, but could, if successful, be expected to revolutionize ecology.

Reflectance, fluorescence, and wing-beat frequencies of well-defined insects can be performed in a laboratory setting in preparation for field experiments. Figure 11 shows examples from such work for three maize pest insects, for which reflectance and fluorescence dorsal and ventral spectra were recorded for male as well as female specimen.\[^{226}\]

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Figure 11. a) Chinese maize pest insects. b) Reflectance and fluorescence spectra of these insects. For further details, see ref. [226].
4.1. Passive Methods, Occultation and Remote Dark-Field Monitoring

In analogy with exoplanet detection\cite{237} aero fauna such as birds can be detected by solar and lunar occultation. The challenge is less trivial than it sounds, since nocturnal migrants cruise at several kilometers altitude. Still, manual observations with binoculars can yield numbers of migrants, direction of flight, rough sizing/ranging, and in some cases classification from the silhouette shape. Large coordinated campaigns with hundreds of distributed observers have been organized\cite{1} and altitude-dependent method biases have been evaluated against radar and thermal methods.\cite{2} The field-of-view of lunar/solar obscuration is limited to 0.5°; this is wide compared to lidar opening angles, but narrow compared to thermal imaging or radar. Migrants transit the celestial dishes on the scale of seconds but typically only obscure a thousand or less of the dishes; therefore a spatially averaged transmission measurement would fail to distinguish a migrant from noise, whereas detection with an imager implies much smaller detection limit. The altitude span of migrants is several kilometers, and using a telescope with a high light-collection efficiency combined with a high-speed camera implies that the migrants are not only extending very few pixels but are also unfocused compared to the celestial bodies. For this reason, shape analysis is less feasible than the utilization of other domains such as the modulation or spectral ones.

Zero-background or dark-field methods, where the field-of-view is terminated in a black cavity, yield improved detection limits; see Figure 13. These setups and methods can be understood as an inverted version of differential optical absorption spectroscopy\cite{39,40} (DOAS), which are realistic and widespread monitors for environmental gases. Dark-field setups typically operate in the near-field regime; thus the probe volume is cylindrical with the width of the telescope extending for a couple of hundred meters. The method can be employed with spectrometers running at some 100 Hz sample rates.\cite{61} For some species this enables determination of sex\cite{61} or species\cite{87} according to the intrinsic coloration. Detection of insects tagged with powder dyes have also been demonstrated.\cite{84} When the fiber spectrometer is replaced by a photodiode followed by an appropriate transimpedance amplifier, the sample rate can be hundred times faster.\cite{84} This enables modulation spectroscopy by which sex or species may be classified.\cite{67,79,80} In Figure 14, a spectrogram is presented of a small prey, presumably a fruit fly or similar, which is followed by a large low-frequency predator, presumably a dragonfly, at the campus of ICIPE, Nairobi.\cite{84} If a quadrant photodiode is employed, range and flight directionality can be assessed.\cite{88} This information can be visualized in color-coded spectrograms,\cite{96,239} despite that insects may seem to intersect the probe volume randomly, statistics of the thousands of insects observed over an hour may shed light on the large-scale movement and dispersal of insects, for example, in relation to migration, pest invasion, or wind conditions. Different insects and stages of insects use wind differently, for example, tailwind for energy saving, headwind for olfactory tracking, and side winds for maximizing encountering of odor plumes. Naturally it can be shown that lateral movement is more frequent than vertical movement.\cite{88} Beam splitters or sandwiched photodiodes (e.g., Si/InGaAs) may be employed to retrieve various broad bands of the scattered
sunlight at kHz rates. An important application of InGaAs detectors and bands in the short-wave infrared, is the assessment of body and wing melanization. Melanin is the most widespread pigment of aerofauna and the NIR/SWIR melanization ratio has been shown to be largely independent of the observation angle, and precise quantification allows distinguishing closely related species. Generally, scattering cross sections cannot be calibrated to absolute units unless the range is known as in lidar. Passive ranging (or passive lidar in analogy with the more widespread passive radar) on aerofauna was initially attempted through the O₂ absorption band at 760 nm, but the results were ambiguous. However, it is possible to calculate the insect range in dark-field methods through employment of a quadrant detector and a correlation method. Such minimal insect monitors may find widespread usage in, for example, agriculture; however, the method has still not been developed for nocturnal species. Passive monitoring can also be accomplished by stereo vision, but unfortunately these studies do not attempt to quantify any optical cross sections.

4.2. Active Methods, Pulsed/Time-of-Flight Lidar

Atmospheric lidars have been developed for aerosol monitoring for several decades. The systems are typically based on Nd:YAG lasers with a low 20 Hz repetition rate.

In radar ornithology and entomology, several studies rely on the exploitation of existing radar infrastructure for meteorology (ENRAM). Both in Europe and America distributed networks of atmospheric lidars operate on a daily basis. The feasibility of using such network nodes for aerofauna studies have been initially studied, although the efficiency and number of fauna observations are limited due to the narrow beam and slow sampling rates and limited range resolution.
Airborne topographic lidar has during recent years shown countless applications for profiling vegetation structure. Although aerofauna is seldom targeted directly in these studies, correlations between vegetation structure and preferred habitats are demonstrated, see, for example, ref. [51]. Reversibly, insect defoliation can also be studied with vegetation profiling lidars, see, for example, ref. [52]. Airborne lidars for bathymetry can in the same way be used to predict abundance of fish and corals in aquatic applications.

4.2.1. Atmospheric Applications of Time-of-Flight Lidars

Monitoring of aerofauna using lidar techniques was pioneered by the Montana group with Shaw et al., performing studies on honey bees, which were trained to detect odors from hidden explosives, in particular mines (see Figure 15). A scanning pulsed Nd:YAG-based system operating in the time-of-flight (TOF) mode at 532 nm, recorded the elastic echoes from bees aggregating in the air above the mines. The Montana group also studied the wing-beat characteristics from honey bees using a CW laser system, as shown in Figure 16. A backscattered waveform with beat oscillations of about 200 Hz is shown in Figure 16b. The group has performed additional studies on honey bee detection; see, for example, refs. [247–249].

The Lund University fauna lidar group published its first insect studies in 2009 pursuing TOF lidar monitoring with a system based on the Lund mobile lidar laboratory, described in ref. [44]. First feasibility studies are reported in ref. [250], and were followed up by a field experiment on damselflies, moving around over the surface of a small river, located about 100 m from the lidar system. The 355 nm radiation from a frequency tripled Nd:YAG laser was employed. As reported above, insects dusted with dyes were also studied in fluorescence. Later, the Lund TOF system was transferred to Hangzhou, China, where studies also on agricultural pests were pursued.

Starting with accidental hits on birds in connection with remote insect studies, the Lund group initiated dedicated work on flying bird detection using TOF techniques. Again, our studies were based on the Lund mobile lidar platform.
fluorescence characteristics of museum birds were studied to build up a spectral catalogue. A field experiment, where many different remote-sensing techniques, such as moon occultation, infrared imaging, and fluorescence monitoring was arranged. Different lidar scenarios for monitoring and identification of high flying migrating birds using the spectral modulation in reflectance induced by the wing beats were investigated. The occurrence of migrating birds in elastic lidar was also investigated.

A vertically sounding elastic scattering lidar system installed for aerosol monitoring was parasitically used for the purpose of aerofauna monitoring. By capturing and analyzing the occasionally occurring very large echoes, information on the passing birds could be attained. Figure 17a shows the set-up used by the Lund group for bird identification based on fluorescence signatures. It used quadrupled Nd:YAG radiation at 266 nm for these measurements, since the more convenient 355 nm tripled output is not necessarily eye-safe for birds, that also possess UV vision capability. The fluorescence echo from a bird is spectrally decomposed into four time-resolved detection channels, selected by means of dichroic mirrors and filters. In this way, the elastic light, and blue, yellow, and UV fluorescence could be simultaneously detected, as shown in Figure 17b, where the results from the release at 80 m distance of a lesser white throat into the laser beam are shown.

**4.2.2. Aquatic Applications of TOF Lidars**

Monitoring of fish using pulsed laser techniques much resembles laser bathymetry, which has been successfully developed to measure the depth of shallow waters, preferably from an airborne platform. Motivations can be to charter unknown underwater structures like shallows or wrecks, which might constitute hazards for maritime transportation. Other motivations could be military ones, like finding out the exact profile of water shallowing up at a coastline in preparation for amphibian embarkation, or for detection of submarines. Whatever the motivation, bathymetry, and thus also fish detection, would be limited to tens of meters because of the very high water attenuation, even in the most favorable blue-green spectral region. The water transmission spectral profile is varying much depending on the degree of water pollution and turbidity. The field has been extensively treated already in the early work of Jerlov. The frequency-doubled Nd:YAG laser operating at 532 nm is frequently a preferred choice. Because of the extensive military interest in satellite–submarine communications, a lot of additional blue-green laser sources for water sounding have been developed, as well as corresponding narrow-band filters for day-light suppression, frequently based on atomic vapor selective response.

The motivations for optical fish detection could be varying. Ship-borne ultrasound devices have reached a high level of sophistication and are clearly hard to replace in the fisheries industry. The detection relies mostly of the acoustic contrast between water and the air in the fish swim bladder.

A motivation for early exploratory fish lidar work by Swedish researchers was for fish inventory in the Baltic sea, where fish during wintertime stay very close to the surface and out of reach for the conventional ship sonar systems. Airborne fish lidar might be a valid possibility for acquiring data as input for international negotiations for fishing quota. Figure 18a illustrates a set-up used in 1978 at a ship-model testing long water tank. A pulsed nitrogen laser operating at 337 nm was employed in exploratory measurements in two geometries, one simulating ship-borne probing and one helicopter-borne measurements. An arrangement of fish, mounted on a plate, was used as a target in the horizontal water probing path. Figure 18b shows the raw lidar recording for the airborne simulation. By transmitting linearly polarized light and detecting the depolarized component, the strong reflex from the surface could be suppressed. The experiment outcome motivated field work based on the Swedish research vessel Argos, where live fish, caught by commercial fishermen, was transferred into a net cage, which was hauled up and down under the vessel while performing laser probing from the ship railing. Figure 18c shows a histogram of echo strengths showing the practical detection of the presence of fish. Recent airborne elastic lidar work with modern solid state lasers have been employed for similar reasons; namely mapping fish intensities at shallow depths, this time in the fresh waters of the Yellowstone park.

Fish species identification by remote sensing would clearly be desirable, and the feasibility of using a fluorescence signature was investigated. Live fish specimen at shallow water depth was used in these experiments. Unfortunately, the fluorescence
of two investigated species turned out to be basically identical, and close to that of the water medium, as illustrated in Figure 18d. This was also the case when studying two different types of common North-Sea species of jelly-fish, *Aurelia Aurita* and *Cyanea capillata*, which were investigated\(^\text{[256]}\) to find out if there was any basis for a remote sensing early warning system for jelly-fish clogging at cooling water inlets, a serious problem for certain nuclear power plants. The outcome was in this case negative. However, certain species of jelly-fish do have strong fluorescence, as found out in other contexts.\(^\text{[175]}\) The nuclear plant cooling issues have again surfaced with renewed actuality, and warning systems based on different technologies are again considered. Maritime species with strong and sometimes characteristic fluorescence are microscopic algae, as studied, for example, in refs.\(^\text{[174–176,190,257]}\), and utilized in airborne monitoring systems (see, for example,\(^\text{[258]}\)). CW lidar technology, to be further discussed below, also allows miniaturized systems for vegetation profiling\(^\text{[193,194]}\) even on drone platforms.\(^\text{[259]}\)

As a side comment, vegetation lidar systems have much in common with aquatic lidars and it is a fairly well developed discipline with both experimental\(^\text{[260,261]}\) and commercial instruments, see, for example, ref.\(^\text{[262]}\). Important fauna applications include correlations of biodiversity to the shape of vertical vegetation profiles.\(^\text{[51,263,264]}\)

Airborne fish detection was first demonstrated in 1981.\(^\text{[266]}\) The development of powerful systems, for example, the NOAA Fish Lidar system by Churnside et al., has led to swift progress.\(^\text{[33,267–272]}\) As an intermediate stage, ship-borne studies (also discussed in ref.\(^\text{[254]}\)) were performed as shown in Figure 19, where fish school lidar recordings are shown and compared with almost simultaneous acoustic sounding.\(^\text{[265]}\)

Illustrations of operational airborne mapping of fish and squid using the NOAA fish lidar system are shown in Figure 20, illustrating considerable range.\(^\text{[271,272]}\)

### 4.3. Active Methods, CW Lidar and Scheimpflug Arrangements

Bistatic lidar was pursued prior to the invention of the pulsed laser.\(^\text{[273]}\) The method relies on triangulation and inferring range from an observation angle and a known baseline separation. In atmospheric lidar, requiring supreme sensitivity to retrieve the molecular echo, this methods was pursued using wide angle cameras, hundred meters baseline and pulsed lasers; still the operation was limited to night time.\(^\text{[274]}\) With inspiration from the laser profiling community\(^\text{[275]}\) and the work of Scheimpflug,\(^\text{[276,277]}\) continuous wave lidars were developed with short baseline and large aperture\(^\text{[219]}\) capable of overcoming the optical background.\(^\text{[278]}\) The systems utilize miniature laser
diodes of several watts of power and can operate at kHz rates over several km\cite{99}. The properties of high spatio-temporal resolution have proven valuable for entomological radars. To date numerous Scheimpflug lidars have been developed and operated in Sweden, Norway, Denmark, England, South Africa, Ivory Coast, China, Tanzania, Colombia, Ecuador, and USA.

Similarly to early entomological lidar work from Montana,\cite{247–249} the method has proven capable of remotely retrieving modulation signatures from insect wing beats. The method has further been extended to include multiband elastic sounding\cite{149,279} and polarimetric retrieval of wing beats\cite{120}. The method has been pursued using both Si- and InGaAs arrays, which cover eye-safe bands in the SWIR region.

For aquatic monitoring, the Scheimpflug lidar method has recently been combined with hyper-spectral push broom instrumentation.\cite{93} In principle, inelastic hyperspectral lidar approaches could also be applied to aerofauna monitoring, in particular to powder-tagged organisms\cite{60,84,183} in order to yield great identity certainty.

### 4.3.1. Atmospheric Applications of CW Lidar

The basic set up of a CW Scheimpflug lidar system is shown in Figure 21a. A CW laser beam is transmitted collimated by a telescope and atmospheric backscatter from the beam is collected by a receiving telescope, arranged at a certain, small separation from the laser transmission telescope in a bistatic lidar way. Sharp image focusing at close, as well as far range from the detector is achieved by tilting the linear, imaging detector, with the geometrical arrangement following principles given by Scheimpflug.\cite{194,277,280} With such an arrangement it is clear that the range resolution is good at close range, and decreasing with range. The same observation leads to the conclusion, that the inverse square distance dependence of the volumetric echo signal intensity in common TOF lidars is replaced by a constant signal at each detector pixel. Modern CMOS detectors allow a read-out rate of the order of kHz allowing the capture of wing beats from insects crossing the laser beam. A particularity of such a Scheimpflug arrangement is that insects, non-resolvable from each other according to common image resolution rules, can still be discerned through their different wing-beat frequency tagging, as illustrated in the figure and discussed in ref.\cite{239}.

Figure 21b shows a 50 m × 200 ms zoomed-in raw data visualization of night-time recordings using the system of the kind described in Figure 21a. Entire datasets extending over days and kilometer ranges have been investigated.\cite{120,145,281} Insect numbers in the order of 10^7 observations per day are reported. On the vertical axis, the frequency content of the
insect echoes recorded at high temporal resolution is displayed, featuring the fundamental frequency and a number of higher over-tones, corresponding to the non-sinusoidal signal from the oscillating wings. The low-frequency noise from the atmosphere and system (pink noise) is seen as a signal floor.

The linear detector, illustrated in Figure 21a, allows kHz recordings of the type shown in Figure 22 to be obtained. Examples featuring a short and a long passage through the laser beam are displayed with overtones, supporting an initial model for heading assessment.[99] A later study[88] concluded that specular scatter contributions induce deviations from this simplistic model.

Further insect signals are shown in Figure 23. In Figure 23a, the oscillating wing-related part and the more static signal due to the insect body can be clearly discerned. Figure 23b gives the two frequency spectra of two insects, which are not optically resolved; a situation illustrated in Figure 21a.

A number of field experiments has been performed to evaluate the potential of the CW Scheimpflug lidar approach for effective insect monitoring.[194,238] Work was performed in Swedish forestry, agricultural biodiversity settings, etc., for example, ref. [281]. Through the collaborative African network AFsin[282] the technology has been effectively disseminated also to low-resource settings, for example, in Ghana, Senegal, Kenya, Ivory Coast, and Mali.[34–40,88,283,284] African aspects include, apart from agricultural pest monitoring, the urgent task of effective monitoring of infectious diseases,[8] such as malaria, spread by insect vectors such as Anophelines.[91,103]

Extensive field work employing CW lidar techniques in insect monitoring was also performed in a rice paddy setting in Southern China.[320,145,285] A particularity of this experiment was that the system allowed full characterization of the depolarization properties of the backscattered radiation. Two identical high-power diode lasers operating at 808 nm and arranged to have perpendicular linear polarizations were intermittently activated, and the depolarization in the light from each particle encounter could be analyzed. This allowed the effective discrimination between insects and raindrops, as illustrated in Figure 24.

The analysis is based on the fact that raindrops scatter light with maintained state of linear polarization while insects, with hairy and irregular surface of wings and bodies, cause depolarization. In particular, we note how a strong rain shower already at its start washes all the insects down, even from high altitudes, clearing the atmosphere of insects.

4.3.2. Aquatic Applications of CW Lidar

While pulsed laser systems certainly have the capability of effective aquatic monitoring, systems are bulky, costly and not suitable for long-term monitoring. Instead, the Scheimpflug CW lidar concept has the potential to be an efficient alternative for short-range monitoring, especially from fixed installations. Such a system can also probe waters with a much higher spatial resolution, which is quite useful, especially in view of the fact, that the attainable range in underwater applications is anyway very limited because of the water optical attenuation. We have made a first demonstration of such technique[93,286] in experiments on a tank of smaller dimension than the one used in the early fish-lidar demonstration experiments.[253] Our experiments are illustrated in Figure 25.

A high-power CW semiconductor laser beam at 445 nm is transmitted through water over a distance of about 5 m, and backscattered radiation is detected by a receiving observing telescope connected to a 2D detector chip in a Scheimpflug geometrical arrangement. In contrast to the systems for atmospheric monitoring, described above, the aquatic system provides multi-spectral recording from each range, by adding wavelength dispersion, achieved by a prismatic system acting in the perpendicular direction to the spatial dimension. In this way, water Raman recordings, useful for attenuation measurements, and fluorescence from algae and marked zooplankton can be monitored[141] as illustrated in Figure 25b. Since the read-out rate is fast, oscillations from flagellates or small fish should be readily detectable. Since the cost of an aquatic lidar of this kind is quite reasonable and the components are robust, wide applications in limnology and marine monitoring could be expected, both for fixed installations and for ship-borne, downward-looking arrangements.
Figure 22. Raw data recordings of two insects passing the laser beam, a) with a short crossing time, b) with a longer one. c,d) The corresponding temporal signals. e,f) The frequency contents as generated by fast Fourier transformation. For details, see ref. [62]. Reproduced under the terms of the CC BY 4.0 license. Copyright 2015, The Authors, Published by Public Library of Science.

Figure 23. a) Recording of the backscattering signal from an insect flying at about 100 m distance, with oscillations due to scattering from beating wings. b) Fourier transform from two insects with fundamental wing-beat frequencies 97 and 63 Hz, respectively. Clear harmonic signals are seen from both insects. Reproduced under the terms of the CC BY 4.0 license. Copyright 2014, The Authors, Published by EMW Publishing.
Figure 24. Monitoring of night-time backscattering events during 1.5 hours in a Chinese rice cultivation setting. Events are plotted separating insects from raindrops by using the transit time through the laser beam (red and blue curves, respectively). In addition, insects were discriminated by their depolarizing properties. It is noted that the insect discrimination works similarly using both methods. Reproduced under the terms of the CC BY 4.0 license.\cite{120,285} Copyright 2017, The Authors, Published by Springer Berlin Heidelberg; and Copyright 2018, The Authors, Published by EDP Sciences.

Figure 25. Underwater Scheimpflug lidar a) hyperspectral lidar instrument, b) experimental bistatic CW set-up, and c) experimental time-range multi-spectral recording of water-Raman and green algae release 5 s after the start of the recording.\cite{93}

As mentioned earlier, post-acquisition focusing on sparse organisms can be accomplished by digital holography.\cite{287} This very simple optical setup is based on imaging transmission using a narrow-band laser. The laser can be CW, but pulsed operation reduce background and motion blur. Holography is based on coherent light and heterodyne detection using a reference branch. However, the reference can be the non-obstructed part of the same beam; this is referred to as in-line digital holography. The method is well developed\cite{71,82,288–290} and includes experimental set-ups and also commercial instruments, see, for example, ref. [291]. The reported instruments and studies are based on a single wavelength and polarization, and species specificity is primarily based on geometrical details but also on movement dynamics. Much of the challenges consist of data processing algorithms for image reconstructions,\cite{82,292} tracking,\cite{75} and shape recognition.\cite{74,289} The technique is particularly suited from small micro-organisms such as diatoms. The method has also been applied for estimating the smaller end of the aquatic biomass spectrum.\cite{26,293} Figure 26 displays various highlights from aquatic holography. To our knowledge, there have been no attempts to apply digital holography to sparse aerofauna.

5. Discussion and Outlook

We have reviewed present work extending small to moderate scale biophotonics to coverage on the landscape level. Inspiration and analogies can be drawn between existing lidar literature\cite{37,45,48,295} and experiments in conventional biophotonics\cite{58,95,112,114} on the micro- and macroscale to envision the opportunities in this emerging field.

When comparing optical methods to radar\cite{4,20,228} and sonar,\cite{27,101} we conclude that the optical windows and instruments are more delicate and easier to contaminate; thus long-term monitoring over seasons and years requires routine maintenance, whereas radar and sonar have produced
observations over years. In terms of aquatic monitoring, lidar could reach considerably deeper than passive satellite imaging. However, the range would never reach that of sonar, see, for example, ref. [27]. When comparing lidar to radar, it currently seems challenging to compete in range with Doppler radars covering hundreds of kilometer range. Although this is in principle possible with lidar, more realistic systems have a range of 2–10 km, which essentially covers the vertical thickness of the aerofauna layer. A particular consideration with laser-based equipment is eye-safety aspects, which are particularly demanding in the 400 nm to 1.4 μm wavelength region.

Lidar systems experience superior beam control and characterization, whereas kHz radars are limited to vertical profiling above 100 m, often related to far distance migration. Lidars can profile animal activity close to the ground and even embedded in forest vegetation structures as long as a line of sight is present. Tracking individuals by powder tagging is applicable to a wider range of animals and implies less perturbation to their natural behavior compared to diode tagging for harmonic radars.

A repeating feature in lidar versus radar and sonar is that optics could provide specificity much beyond the possibilities in the microwave regime and acoustics. This is because light interaction with animals is highly dependent on the wavelength according to molecular absorption in the tissue and resonances in the microstructure, and fluorescence provides further tagging possibilities. The orientation of co-polarized of microwaves is sometime employed in radar for heading assessment, whereas reporting depolarized microwaves is scarce. In the optical region, depolarization can shed light on the target characteristics. As opposed to acoustics and microwave technology, photonics provide simple and miniature means to apply diverse spectral content and depolarization modes.

The field of biophotonics has primarily been associated with the white biology community (lab coats), whereas the presented activities tie themselves toward green biology (rubber boots). Although, laboratory studies are characterized by supreme experiment control and convenient distance to the coffee brewer, outdoor field work brings the rare joy of laser physicists to work in nature, with supreme earth connection and a chance to grasp nature as it is.

Cross sections for nuclei, atoms, and molecules are tabulated in reference works such as HITRAN. Efforts to report on standardized cross sections on feasible wavelengths for
animal species of key importance should be encouraged. Even a sparse database on distinctions between species would allow for interpolation and rough classification to family, if not species.

An important aspect is that abundance observations are biased by the instrumentation in several domains; organisms falling under the detection limit will not be observed and the cross section detection limit depends on range\cite{281} but also on optical background noise, which varies over the day.\cite{115} The likelihood of animals to intercept the probe volume depends on the size and shape of the probe volume, for example, in a divergent laser beam. Even in the frequency domain, the reflected light spectrum is normalized by the instrument efficiency curve. In relation to correct frequency analysis in modulation spectroscopy on animals, several lessons can be learned from system identification, noise analysis, and information criteria.

Overall, employed optical approaches for fauna monitoring vary in collection efficiencies. The methods with some strategy for focusing on the sparse structure of fauna seem particularly promising. For example, both digital holography\cite{292} and Scheimpflug approaches\cite{281} can report on large number of observations from small periods. The effectiveness and feasibility may, however, differ widely depending on the application and aim. For instance, the simultaneous recording of long flight trajectories demonstrated by thermal infrared stereo vision\cite{209} could not be accomplished by laser-based methods anytime soon.\cite{212} Biologists are keen to adopt the simplest and most straightforward technology such as stereo vision in the field, but more information could be extracted by accurate analysis of optical signals and cross sections from these approaches. kHz frequency-domain methods such as e-traps\cite{68,79,80} and entomological lidars\cite{239,301} have proven efficient in distinguishing insects, whereas applications to birds, bats, and aquatic life are less reported. Despite fast optics developments, there are severe mathematical challenges such as the pitch detection problem\cite{102} and proper exploitation of phase information in harmonic spectra which is currently discarded. It is worthwhile to team up with experts in signal processing and speech recognition. Despite much laboratory work, the polarization- and spectral domain remain rather unexplored for remote sensing of animals and leave much room for experimental laser physicists for development. For aquatic monitoring, the new inexpensive and compact high-power violet and blue GaN laser diodes and CMOS sensor technology open up for significantly simpler\cite{93,303} and more widespread instrumentation than what is the case for previously employed pulsed lidar. Finally, emerging technologies such as drones,\cite{259} distributed sensors,\cite{304} Raspberry, Arduino, and low-cost Global Open Source Hardware instrumentation\cite{305} are likely to increase the creativity and wealth of information on animal ecology in the years to come.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

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