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Radar as a Key to Global Aeroecology: Essentials of Technology and Development Milestones

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ABSTRACT

Open, systematic, and global approaches are needed to address the challenges of aeroconservation and pest management. Recent technical progress enables deeper investigation and understanding of aeroecology. Radar plays a central role in flying species monitoring in the global scope. The technology provides various ways of targets detection and tracking, working for multiple ranges and different visibility. The existing technology allows deploying global monitoring of avian and insect species. This work discusses the essentials of the technology and the history of its application for bird and insect detection. The author describes the development of the topic according to the main groups of radar approaches: pulsed sets, vertical-looking solutions, harmonic systems, and efficientfrequency modulated continuous wave radar. Advances in big data processing, robotics, computation, and communications enable practitioners to combine the discussed radar solutions aiming at global avian and insect biodiversity monitoring and negative human impact systematic estimation.

Keywords:Aeroecology, Small Species Monitoring, Birds, Insects, Pulsed Radar, Vertical-Looking Radar, Harmonic Radar, Frequency Modulated Continuous Wave Radar

INTRODUCTION

Nowadays, damaging human impact on nature is one of the main concerns. The discussion regarding global warming is highly distinguished in this context. Uncountable pieces of evidence confirm human destructive effect to nature which must be reduced and controlled immediately (McKibben, 2003). Researchers come off from the small to large scale. The investigation started from global climatology, deforestation, desertification gradually increases the details.

The recent progress in information and communications technology allows us systematically consider even hardly observable worlds. One of such vital worlds is the world of birds and insects. Bird and insect conservation is possibly one of the most critical and urgent questions in this regard. In general, conservation biology stands for a relatively recent, synthetic field that applies ecology, biogeography, population genetics, economics, sociology, anthropology, philosophy, and other disciplines maintaining biological diversity throughout the world (Groom et al., 2012). It is motivated by human-caused global changes that have resulted in the most remarkable episode of mass extinction since the loss of the dinosaurs 65 million years ago. One can notice that in the frame of conservation biology, bird and insect conservation does not occupy a significant part, but, with the mentioned technological progress, it becomes more and more distinguished and recognizable.

Researchers distinguish two main ethic approaches regarding insect conservation: Romantic-Transcendental Preservation and Resource Conservation. The former consider insects a significant part of the ecosystem without intention to affect, intrude or fix something. The latter stands for sustainable utilization of insects. The Romantic-Transcendental Preservation Ethic is especially actual in the context of the nature reserve. Lockwood (2005) has formulated a strong ethic concerning insects, which says that actions that may be reasonably expected to kill or cause nontrivial pain in insects when avoiding these actions have no costs to our welfare have to be minimized. In that regard, our attitude to *Basking malachite* (*Chlorolestesapricans*, an attractive South African damselfly on the verge of extinction) and citrus wax scale (*Ceroplastesbrevicauda*, pests on a citrus twig) should tend to be equal (Samways, 2005). Additionally, many emphasize the need for balancing conservation and pest suppression. Regarding this, New (2018) wrote: "Harmonising pest management and insect conservation pose problems in many contexts in which human economic priorities, essentially protecting supplies of food or commodities such as timber, can come into conflict with conservation ideals." The same ideals should be applied for bird conservation.

Nowadays, all regions concern the bird and insect conservation problems leading to worldwide changes. For instance, McLean et al. (2012) discussed the rich evolution of the UK movement for invertebrate conservation actively, which has been developed from the middle of the 20th century, consolidated in stature through decades, and then diversified and supported more firmly the voluntary sector. Pyle (2012) described the origins and history of insect conservation in North America in the damaging European colonization. Many works provide similar concerns for other regions (e.g., New Zealand (Watts, 2012), Central Europe (Spitzer, 2012), Japan (Ishii, 2012), etc.). Most of the works take into account specific species.

"Fine-grain" conservation with the particular species focus often attracts more extensive interest since it can provide concrete results. Such an approach is especially actual concerning insects about extinction. New (2009) provides a detailed "fine-grain" methodology and solutions applied for various species in Australia. He discusses criteria for assessing priority for advisory or legislative categorization of threatened or protected species, conservation plans, needs in planning habitat and resource supply, and insect management plans for the future. Moreover, he discusses monitoring roles in conservation management. In this regard, the monitoring prevents insect management from being rigid and leads to adaptive and periodically or continuously dynamic management.

Usually, researchers tend to conduct monitoring periodically, arguing time intervals depending on the object and resources (Hauser et al., 2006). Traditional monitoring requires significant resources. Often, such intervals are annual, which makes it impossible to distinguish large-scale processes limiting understating of various trends. Recent progress in technology dramatically reduces prices for electronic devices and data processing. That leads to dramatic changes in approaches to insect and bird monitoring with potential real-time solutions.

RADAR'S ESSENTIALS

With technical progress and reducing prices for electronic components, radar technology becomes very popular in environmental monitoring research. In comparison to other remote sensing solutions, radar concepts seem more complex and specific. Thus, compact and descriptive introductory information is required. In this and the following section, the author tries to meet these expectations aiming at practitioners without a satisfactory technical background. Shortly and descriptively, he defines radar, describes its history, fundamentals, radar types, signal processing, and applications.

Radar adopts electromagnetic waves in the radio range for object detection. It can measure the parameters: the range (distance to an object), angle, and velocity (radial speed). Radar has multiple applications. As many technologies are designed for military purposes, radar facilitates various civil tasks, from aircraft navigation to environmental monitoring. To effectively utilize this technology (for environmental monitoring in particular), it is crucial to have a systematic overview of radar history and fundamentals. What is more, the basic principles of radar data processing play a crucial role in such studies.

Brief History

Radar was originally developed for military tasks. United States Navy started to use the term "RADAR" as an abbreviation of RAdio Detection And Ranging (Parker, 2003). Now, the term is used as a regular English noun spelling in low-case.

At the end of the 19th century, Maxwell (1892) proposed equations concerning the behavior of electromagnetic radiation called Maxwell's equations. These equations establish a fundamental theory for electromagnetic phenomena and their applications. The equations are fundamental for uncountable technological solutions using the electromagnetic field. One of the first researchers who noticed the ability to utilize radio waves for object detection was a Russian scientist Alexander Popov (Kostenko, 2001). In 1892, he reported an interference beat caused by the passage of a third vessel and the potential usability of this for object detection.

In 1904, Christian Huelsmeyer (van Loon, 2005) (for the first time in history) showed how to use radio radiation for the detection of distant metallic objects (ships) in dense fog. He proposed the use of radio echoes in a detecting device designed to avoid collisions in marine navigation (Rahman, 2019). One can say that this was a starting point of radar history.

Since then, radio waves have been under severe considerations worldwide. Before the Second World War, the United Kingdom, France, Germany, Italy, Japan, the Netherlands, the Soviet Union, and the United States intensively developed radar and related technologies for their armies (Watson, 2009). These countries massively applied radar technologies in World War II. In 1945, the US Army Air Force issued a report (currently unclassified) systematizing significant variations of available radar and related equipment (USAAF, 1945).

After the war, the utilization of radar has been increased dramatically. Many civil fields have successfully adopted radar technologies. Since 1950, the Doppler principle to radar became popular in the operation of many radar systems (Neng-Jing, 1995). It includes moving target indication, continuous wave, and pulse Doppler radars. In the 1970s, radar systems conduct remote sensing tasks from aircraft and satellites (e.g., the Seasat mission (Born, 1979)). Since the 1980s, phased-array radars facilitate environmental research (e.g., wind speed, ocean waves, sea ice, etc.).

Computer technology that becomes available in the 1990s facilitates retrieving the information about the nature of targets and the environment derived from radar echoes. Also, Doppler weather radar systems applied computer technology to measure precipitation and wind speed. In addition, radar-based altimeters, scatterometers, and imaging radar systems are now widely recognized as highly successful tools for earth observation from aircraft and satellites (Rahman, 2019). Nowadays, radar is a state-of-the-art technology applying in the uncountable military, civil, industrial, and research fields.

Fundamentals

As mentioned, Maxwell's equations are a basis for radio, television, radar, satellite communications, cellular phones, global positioning systems, microwave heating, and X-ray imaging, etc. Radar is usually described as a detection system utilizing radio waves for range, angle, or velocity of objects definitions. Radar uses the emitted waves' refection as the main principle for its work.

To illustrate this, imagine one staying on the low bench of a wide river, a high bench on the opposite side. How can she measure the river's width without any instruments (Perlya, 1955)? To answer this question, one can remember the following trick from childhood: a distance to lightning equals the number of seconds between seeing lightning and hearing thunder multiplied by the speed of the sound. Thus, if there were 4 seconds, the distance is about 1.2 km (i.e., 4 s x 0.3 km/s). This trick allows calculating the distance to a coming thunderstorm.

Concerning the example with the river width, one can yell "Hey!" and start counting seconds. After some seconds, she will hear the echo; usually, it will be "ey." Knowing the number of seconds, she can easily (but approximately) calculate the distance sound passed. The division of this distance by two is the width of the river. The sound, first, goes from the transmitter (the mouth) reaching the target (the high bench on the opposite side of the river). The sound reflects from the target and goes back to the receiver (the ears). The signal is processed by the indicator (the brain), which calculates the distance. For instance, if 5 seconds is required, the river's width is about 0.75 km (i.e., (5s x 0.3km/s)/2). Figure 1 visualizes the discussed example. It is well known that echolocating animals intensively use the described principle. Bats and dolphins (Liu, 2010) emit the ultrasound for orientation in low-visibility and hunting.

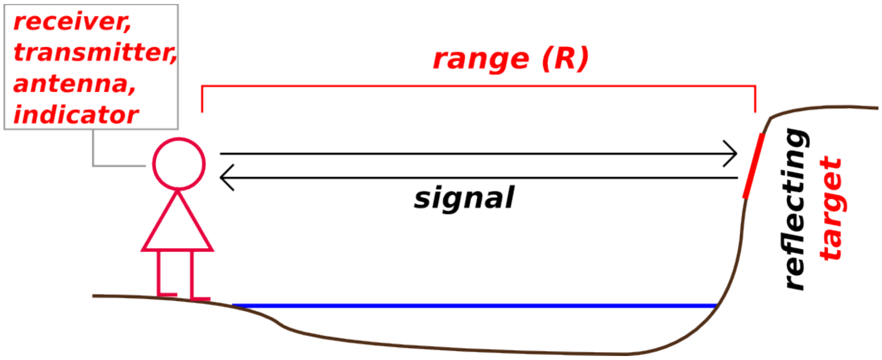

Figure 1.The illumination-reflection principle for the rangedefinition.

Using this simple illustration, we have introduced several important terms: "transmitter" (emitting waves), "target" (reflecting waves), "receiver," and "indicator." Moreover, the described example allows us to write the following simple equation for the range calculation using radar:

$$R=\frac{t_d \cdot c}{2}$$

where, t_d is a time, c is the speed of the light, and R is the desired range). The speed of the light is used because radar radiates electromagnetic waves in the radio range of the spectrum. Radar belongs to the illumination-reflection systems. In such systems, an agent catches reflected from target waves emitted earlier by this agent. The illumination is directing artificial radio waves towards objects.

Furthermore, one important fact should be clarified. Researchers usually describe the electromagnetic waves using either the wavelength (λ) or frequency (f in Hz or s-1). Since electromagnetic waves are distributed with the speed of the light (c), any of them can replace the other according to the following equation: $\lambda \cdot f = c$. Radio waves considering in this article have a wavelength interval from 1 mm to 10,000 km or a frequency interval from 300 GHz to 30 Hz.

As mentioned, the transmitter emits radio waves (or radar signals) in predetermined directions illuminating desired targets. They scattered and reflected in multiple directions. Objects comprising electrical conductive materials (e.g., metals, water) have high reflectivity of radar signals. Other materials are absorbable and penetrable (or even transparent) for radio waves. Considering this more deeply, one can notice that this subject is not straightforward. Many works concern the properties of materials and objects relating to their ability to reflect-absorb-penetrate.

Many works have recently addressed the properties of buildings affecting the extremely high-frequency radio waves (especially actual for mobile networks). For example, Choi et al. (2015) investigated the properties of several materials for the 1mm wave realm: glass, tile, plasterboard, marble, wood, concrete. They examined these materials for reflectance and transmittance using various incidence and reflection angles. Because the angle significantly affects to results, minimal and maximal values are provided in such investigations. They disclosed that glass has the minor transmission loss, and concrete has the most significant transmission loss. Moreover, in the reflection characteristics, glass has the most negligible reflection loss, and wood has the most significant reflection loss on average.

Coca et al. (2014) investigated the electromagnetic waves reflectivity in the frequency interval from 2 to 3 GHz. They showed that melamine hardboard reflects nearly as well as aluminum. The former is one of the best reflectors. Their results also confirmed a fairly significant dependence of reflection properties on frequency, as reflected power decreases with frequency. In that work, the authors provided evidence of the complexity of the reflection phenomena.

Many researchers investigate the scattering and absorbing phenomena, which complete the reflection research. Lonnqvist et al. (2006) measured reflectivity of various radar (310 GHz) absorbing materials. The "radar cross-section" (Knott, 2004) and "radiation-absorbent material" terms play an important role in such research. The former describes the detectability of an object by radar. A larger value indicates a higher detectability of an object. The latter stands for a material that has been specially designed and shaped to absorb radar emitted radiation. Early radars used long wavelengths larger than the targets and, thus, received an unclear signal. In contrast, many modern systems use shorter wavelengths (a few centimeters or less) to detect small objects.

Noise, inference, and clutter are three phenomena that interrupt the correct target detection (Watts, 1987). Electronic components are the source of signal noise. The noise is an internal source of random variations in the signal. Interference occurs when two waves move simultaneously through a medium. The waves interacting with each other can originate from two or more sources. Clutter stands for radio waves returned from uninteresting targets. Moreover, many works investigate the radar jamming phenomenon. Radar jamming is an active, either intended or unintended (deception), inference emitting in the radar frequency and masking aiming targets (Lothes et al., 1990).

If desired targets can be detected despite the described obstacle factors, another rising question is the distance measurement. Classically, radar transmits a short pulse of the radio signal and measures the time allowing the distance calculations. Longer times between pulses enable us to maximize the range. Each radar uses a specific type of signal; long and short ranges are distinguished. Modern types of radar use frequency modulation (Galati, 2017). They consider the frequency shift to measure distance.

Usually, radar is described through the classical radar range equation aiming at maximal range estimation (Richards et al., 2014;TutorialsPoint, 2021):

$$R_{max}=\sqrt[4]{\frac{P_t \cdot G \cdot \sigma \cdot A_e}{(4\pi)^2 \cdot P_r}}$$

where, R_{max} is the maximal theoretical range (distance from the radar to target), P_t and P_r is transmitted and received power, σ is a radar cross-section (or scattered coefficient) of the target, G is gain of the antenna and A_e is the effective aperture of the receiving antenna.

Often, this equation is represented in the following form of theoretical maximum range equation (Wolff, 2009a):

$$P_{rx}=\frac{P_{tx} \cdot G^2 \cdot \lambda^2 \cdot \sigma_t}{(4\pi)^3 \cdot R^4 \cdot L_s}$$

P_{rx} is the power returned from a target. P_{tx} is the powertransmitted by radar. G is the antenna gain (known value), i.e., antenna's abilityto focus outgoing energy to a given direction. Antenna aperture($\frac{G \cdot \lambda^2}{4\pi}$) measures the effectiveness of receiving theincoming signal. σ_t is a radar cross-section or, in other words,the target's reflection ability. Measures can normally define it. Free-space path loss, denoted by $\left(\frac{1}{4\pi R^2}\right)^2$, is the electromagnetic wave in the free spacewithout obstacles. $\frac{1}{L_s}$

summarizes all loss factors; it iscalled external and internal losses. Using provided equations, one can estimate various important theoreticalvalues applicable for estimating the radar use and possiblelimitations.

In radar, the range typically represents the slant range of the target. Rangingis one of the main purposes of radar. Slant range is defined using the described earlier equation ($R=\frac{t_d \cdot c}{2}$). For the pulse radar, τ stands for pulsewidth, i.e., a time required for pulse radiation. The time interval betweentwo consequent pulses is called pulse repetition time (PRT). Thecorresponding pulse repetition frequency is calculated as $PRF=1/PRT$. PRT comprises receiving time and a short interval of resttime ($t_{recovery}$). The maximal unambiguous range is depicted as $R_{unamb}=\frac{(PRT-\tau)\cdot c}{2}$. Minimal detectable range equals $\frac{(\tau+t_{recovery})\cdot c}{c}$. For instance, it equals about 150 mfor a short-range system with 1 μs pulse width.

The antenna's orientation defines the direction to a target; this can also be described as bearing. Using the elevation angle and the altitude of an antenna, the target's absolute height is determined. The accuracy of derived values is determined as the degree of conformance with the estimated and true values. The radar resolution cell defines a volume where targets cannot be distinguished and visualized as a single target. Range and angular resolutions determine the resolution cell.

Speed measurement is another aim of radar. The most straightforward is to mark two positions of a target and, then, knowing a time interval and distances between two states, the speed calculation becomes obvious. Such an approach applies to a well recognizable and trackable target. In many cases, instant speed detection is required, e.g., for the police radar use case. For this, radar utilizes the Doppler effect. The Doppler effect (Serwayand Vuille, 2017) is the change in wave frequency reflecting from the target object. Increasing and decreasing in frequency indicates decreasing and increasing distance from the observer to the target. Many modern radar systems use this principle in Doppler and pulse-Doppler radar systems (weather and military radar). However, the Doppler effect can only determine the relative speed of the target along the line of sight from the radar to the target. The speed measured using the Doppler effect is called "velocity." The following equation describes it mathematically:

$$f_d=f_0'-f_0$$

where, f_d is a Doppler shift, f_0' is frequency of the returnedecho and f_0 is the frequency of the transmitted signal.

Radar Types

Wolff (2009b) introduces a systematic classification of radar systems (see Figure 2), where he proposes two main groups: imaging and non-imaging radar. The former conclude systems producing map-like visualization of the area covered by the radar beam. The latter considers one-dimension measures (e.g., speed gauges and radar altimeters). In primary systems, the target acts as a passive reflector. In secondary, targets emit an active response. Aviation actively uses this principle: airplanes are usually equipped by a transponder (transmitting responder) onboard, and this transponder responds to interrogation by transmitting a coded reply signal. Pulse radar transmits a high-frequency impulse signal of high power. Pulse systems are divided into two categories: pulse and intrapulse modulation. The former utilizes a wave-shaping process produced as a propagating waveform modified by the electrical network properties of the transmission line; the pulse is internally modulated in phase or in frequency, which provides a method (Intrapulse Modulation) to resolve further targets providing overlapping returns (Wolff, 2016).

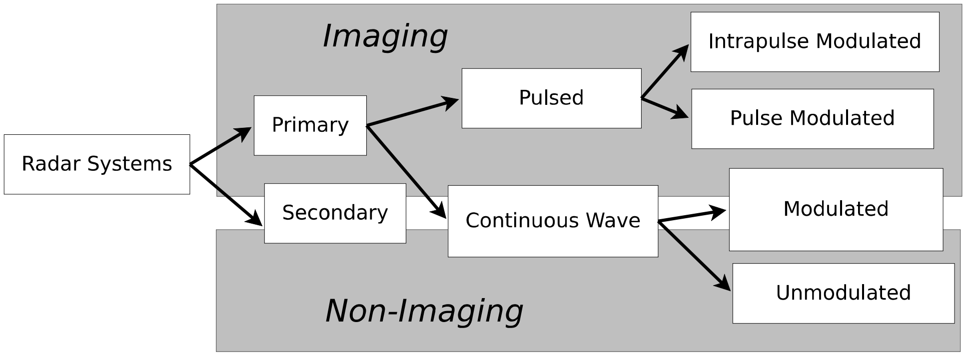

Figure 2.Radar types.

In contrast to pulse radar, continuous wave (CW) sets transmit a high-frequency signal continuously. Thus, there are two primary classes of radar: CW and pulsed. CW sets are cheap and straightforward but generate less information than pulsed radars. In addition, CW systems operate with low peak powers. Conversely, pulsed radars require extra hardware in comparison to CW and operate at high peak power levels.

Early radar versions were based on the transmission of the CW energy and the reception of reflected energy from a moving target (Rahman, 2019). A shift in frequency from the transmitted frequency by an amount known as Doppler shift is the essential basis for CW radar sets. Nowadays, CW systems remain popular and gain high interest. Particular aims determine whether CW or pulsed systems are to be used. The following advantages of CW radars over pulsed radars can be distinguished: simpler and smaller hardware required for CW sets, lower transmitted power level, the shorter range of detecting targets. However, unmodulated CW radars cannot measure the target range. CW systems modulating the signal in amplitude, frequency, or phase overcome this limitation in frequency-modulated CW (FMCW) radar sets. Linear, beat, and sinusoidal modulations are distinguished. FMCW radars use the linear frequency modulation (LFM) technique to measure the range and the Doppler effect.

In addition to the proposed classification, the following types of radar can be distinguished: monostatic, bistatic, and MIMO radars (according to the physical configuration of the transmit and receive antennas), search, and tracking radars. Furthermore, frequency bands, waveforms and pulse rates, and specific applications are utilized to distinguish radars' types. Figure 3 provides a generalized overview of radar frequencies and the electromagnetic spectrum.

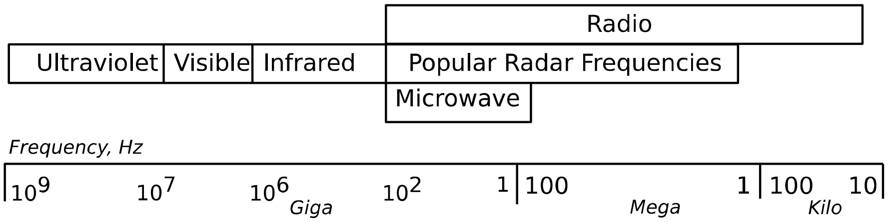

Figure 3.Electromagnetic spectrum and radar frequencies.

Among various types of radars, ultrawideband radar is an outstanding type; it has a high potential in natural sciences. According toTaylor (2016), ultrawideband (UWB) radar is designed to provide X-ray vision into the ground, solid materials, and walls. Such systems have various attractive use cases: remotely measure vital human signs in hospitals (Anishchenko, 2016) and hazardous environments, search for concealed weapons on people passing through a security checkpoint, make high-resolution images of satellites at synchronous orbit range under all weather conditions, locate soil disturbances to find buried objects (ground-penetrating radar) (Taylor et al., 2016), etc. UWB emits a signal with a fractional bandwidth b_f greater than 25% of the center frequency. This meant the signal absolute bandwidth b divided by the signal center frequency f_c, gives the following equation:

$$b_f = \frac{b}{f_c} = \frac{2 \cdot (f_h - f_l)}{f_h + f_l}$$

where, f_h and f_l describe the upper and lower frequencies, correspondingly.

Signal processing and applications

Until this moment, the article considered mainly radar itself. Here it starts to discuss objects detection and radar signal, and data processing. A combination of signal and noise is a significant part of signal processing, where the noise component is a random process. The signal may be deterministic (for countable point targets) or stochastic (for uncountable volume scatter) (Hysell, 2018). Detection theory considers these areas. Radar cross-section (discussed earlier) and signal-to-noise ratio (SNR) are two essential terms of detection theory. The latter stands for a measure that compares the desired signal level to the level of background noise. In general, a signal can be distinguished from noise if SNS is higher than 1:1. It should be noticed that many pulse radar systems are threshold-based (i.e., a signal is distinguished from noise by a predefined threshold). Nowadays, more complex solutions are applied regularly.

Radar sets use a matched filter to decrease noise in receivers. It serves as the signal processor for the case where the radar bases detection decisions on a single pulse (Budge and German, 2015). The matched filter maximizes SNR, which is a requirement for maximizing detection probability. First, the amplitude detector determines the magnitude of the signal coming from the matched filter. Then, the threshold device processed the output of the previous process in a binary decision manner.

Signal detection logic determines four detection cases. First, signal-plus-noise larger or equal than a threshold indicates a correct detection. Second, signal-plus-noise less than a threshold is a missed detection event. Third, noise larger or equal than a threshold causes a false alarm case. Finally, noise is less than a threshold is for no false alarm. The first and the last cases stand for desired events. Detection (the first case) and false alarm probability (the third case) are notated correspondingly:

$$P_d = P(V \geq T)$$

$$P_{fa} = P(N \geq T)$$

where, V is signal-plus-noise voltage evaluated at a specific time, and N is noise voltage evaluated at a specific time. One can notice that P_d increases as SNR increases. That is the reason for including the matched filter in the receiver. It can be included immediately before the signal processor or as a part of the signal processor.

There are several techniques for P_d improvement using multiple transmit pulses: coherent integration (North, 1963), non-coherent integration (Swerling, 1960), m-of-n detection (Schwartz, 1956), and cumulative probability (Hall,1956) prediction. A coherent integrator is a type of signal processor that resided between the matched filter and amplitude detector. Such a coherent integrator accumulates the n-pulse sum and forwards it to the amplitude detection and threshold check. A non-coherent integrator is placed between the amplitude detector and the threshold device. The term "non-coherent" is used because the signal loses phase information after the amplitude detector. m-of-n detection is used as a logic process, not a device; radar examines the output of n-pulses and declares the target detection on any m of these pulses. Cumulative probability stands for the probability of increasing using multiple detection attempts. Various types of signal processors implement considered techniques.

The ambiguity function is utilized to understand the reaction of a signal processor to a given signal. The ambiguity function is a response of a signal processor to a radar waveform. Such function "provides a wealth of information about radar waveforms and how they interact with the environment and the radar signal processor" (Budge and German, 2015). Equations of the ambiguity function can be provided for either unmodulated (more straightforward case) and modulated pulse. Here, the "modulated" term means that the waveform coding or phase modulation is applied to transmit the pulse. Frequency modulation is widely used in CW radar sets since unmodulated CW cannot measure the target range. Linear and sinusoidal (nonlinear) frequency modulations are distinguished. In both cases, a time delay (Δt) allows calculating the range as follows: $R=(\Delta t \cdot c)/2$.

Hysell (2018) has published an extensive introduction to radar and its applications to environmental research. He noticed early radar environmental applications concerning atmospheric experiments by Gregory Breit and Merle A. Tuve in the 1920s. They showed how pulsed radio signals could be used to measure the ionospheric structure measured by "ionosonde" (actually, pulsed radar). Since that time, radar remains extremely popular in environmental monitoring, including the following applications:

- Weather and boundary-layer radar.
- Mesosphere-stratosphere-troposphere (MST) radar.
- Meteor-scatter radar.
- Ionospheric sounders.
- Coherent- and incoherent-scatter radar for ionospheric and space-weather research.
- Radar imaging, including SAR, InSAR, and ISAR
- Planetary radar.
- Ground-penetrating radar for archaeology, paleontology, and Earth science.
- Radars for ornithology, entomology, and other wildlife.

Meteorological objects were observed by the radar massively during its earliest military utilization (especially World War II). Attempts to mitigate the effects of the radar clutter related to the weather lead to weather radar. It remains the most popular radar application in the environmental context. One can distinguish the following representative diameters (in mm) of hydrometeors detected by radar: fog, mist, drizzle, light rain, heavy rain, graupel, hail, sleet, and snow. One of the main goals of radar meteorology is the estimation of rainfall rates from radar echoes. Another goal is the estimation of wind speed and direction (Hysell, 2018).

Another big block of radar applications is radar imaging. It utilizes spatial diversity, transmitters of opportunity, synthetic apertures, multiple antennae pointing positions. Due to these properties, radar can produce a spatial image. For this, radar uses interferometry. It is caused by the physical effect of the superposition of waves from the source vibrating with the same frequency and amplitude (Serway and Vuille, 2017). The interferometer provides a complete range, bearing, and Doppler frequency information for a single target. Image reconstruction based on interferometry with multiple baselines is called aperture synthesis imaging. Synthetic aperture radar (SAR) sets allow airborne and space-borne systems with basic antennas to produce images of distant targets with a high spatial resolution (it is possible to reach 10 cm dimension from a satellite). Such systems take samples of fixed targets at different points along the vehicle trajectory. The enormous size of a required synthetic array affords satisfactory resolution. SAR data are popular in environmental studies. For instance, European ERS-1&2 (inactive today) SAR data are utilized for deriving digital elevation models and their dynamics for glaciers dynamics monitoring (Rao, 2004). Nowadays, famous Sentinel-1 data are utilized for flood research (Clement et al., 2018).

AEROECOLOGICAL RADAR’S DEVELOPMENT MILESTONES

The last radar application mentioned earlier, “Radars for ornithology, entomology, and other wildlife,” is mainly represented by aeroecological radar (i.e., radar aiming at small flying species, like birds, bats, insects). This topic is already mature but remains very promising due to advances in computers, robotics, and data processing.

Crawford (1949) was possibly the first author who showed that radar could detect as small targets as individual insects. In 1950, Rainey (1955) proposed to use radar for insect swarms. He found that if radar can detect the echo from raindrops, it might detect flying locusts. In the following works, Rainey confirmed it. Later, many studies focused on insect swarm detection with radar.

On the other side, in the 1950s, several works suggested using radar for individual insect detection Plank (1958; Tolbert, Straiton, and Britt 1958). This was finally confirmed in the 1960s. In 1966, Hajovsky et al. Hajovsky, Deam, and LaGrone (1966) discussed the magnitudes of the insect cross-sections and the effects of incident electromagnetic energy polarization along with physical characteristics of the insects. Next year, Glover Glover and (U.S.) (1967) published a book discussing tracking single insects in the atmosphere.

Riley (1980) summarized the early history of insect radar. He distinguished two categories of field trial works conducted in the 1970s: ground and airborne radar. That was an outbreak time for radar entomology; many studies were carried out in Africa and Australia. From that time, wingbeat frequency has facilitated distinguishing birds and insects; it was an outstanding achievement. Moreover, Riley (1980) discussed the following topics: resolving insect species using the size or (even) wingbeats(Schaefer, 1976), aerial density measurements for individually resolved targets Riley (1979) and dense concentration Battan (1973), airspeed and heading Riley (1979; Greneker 1978), and, finally, duration and range of flight Schaefer (1976).

Pulsed Scanning Radar

Riley (1985) discussed insect cross-section. In that work, the author developed some findings of an earlier work (Riley et al., 1979), where vertical radar's rotating and linear polarization were utilized to measure individual insect alignment and parameters related to body shape. The authors summarized a tree-year work and concluded that it is possible to detect insects approximately using wingbeat frequencies. Moreover, they investigated the takeoff process (systematic increasing of target heights during observation), the connection of the temperature and several insects in the air, orientation and displacement direction, and migration. Finally, the authors showed how to derive the wingbeat frequency from radar data. The wingbeat modulation and large amplitude "polarization" modulation were distinguished. The former refers to the wingbeat; the latter represents the target size.

Additionally, they introduced the "body shape factor" or radar "signatures" obtained by recording the signals returned from insects flying through the stationary radar beam. The authors made a logical observation that short, thin targets produce deeper modulation than short fat. Riley (1985) systematized insect cross-section data and collated it with the available literature. For several insect species, he showed the variation of radar cross-section as a time function of the angle between a body axis and beam vector ("E-vector"). Furthermore, the author collated his data with other available cross-section data, build a graph of the cross-section and mass dependency, and derived a function ("insect radar cross-sections as a function of their mass"). He concluded "that the radar cross-section of an insect may be very approximately represented by that of a spherical water droplet of the same mass, and that this representation holds true over a mass range of 10000:1" and "the aspect dependence of radar cross-section affects insect detectability."

In the 1980s, insect radar was already wildly spread. In addition to the earlier discussed works, some can notice works conducted in America (Mueller and Larkin, 1985) and Australia (Drake et al.,1981). The former work considered dual-polarization radar utilized in central Illinois (USA) during clear nights and ensured that the received echo was from insect rather than atmospheric turbulence or birds due to the magnitude of differential reflectivity, absence of bird wingbeat signatures, the strength of the signal return, and migration schedules of birds in the research area. The later work described research covering Bass Strain (Australia). This work differs from all earlier mentioned. It is very geographical oriented; the authors thoughtfully adjusted their radar data with atmospheric processes and light-trap catches, resulting in a severe scientific basis. Drake et al. applied an entomological pulse radar device operated on a frequency 9.5GHz (X-band, 3.2 cm wavelength) with a nominal peak power of 20kW. They confirmed massive takeoff of insects shortly after sunset observed earlier by many other researchers. Moreover, they noticed a migration from the mainland, and the immigration of targets from nearby source areas was often observed on the radar.

Vaughn (1985) published a review on the radar for birds and insects summarizing relevant achievements known by that year; the author reviewed radar cross-section measurements of birds and insects. He proposed to describe targets either as a prolate spheroid or, due to linear horizontal polarization of many targets, resonant half-wave dipole. Vaughn stated that a comprehensive review of radar entomology is premature because entomologists could learn little about insects except for the problem of either detecting or not detecting these targets. One can disagree with this statement because, as was shown, many earlier works investigated very new aspects of insect behavior with details unknown before (e.g., migrations, takeoffs, etc.). The work showed that flocking and swarming properties of targets are very beneficial for detecting targets on large ranges; the author applied different radar types (0.25μs 1.24º half-power beamwidth ground-based radar, surveillance FAA radar, modified A-scope X-band marine radar). Vaughn described in detail the early history of establishing the entomology radar (we propose to use as a complete review source for that historical period of insect radar); many of the works he cited we have discussed earlier.

The previous work discussed birds and insects together. Indeed, due to the similar behavior of targets, radar entomology and ornithology are very close disciplines. Larkin (1991) admitted a mistake that many of the targets previously considered as birds were actually insects. It leads to a significant revision of his initial findings. The lack of wingbeat patterns of birds, radar-controlled high-power telescopes and spot lamps, and speed and abundance (preferably, in warm months) of targets spotted this problem. As discussed earlier, cross-section (σ) allows estimation of target size and wingbeat patterns; that applied the discrimination of birds from insects. Graphs of distinguished "birdlike" and "insect-like" targets showing the number of tracks versus speed of flight and the number of targets versus radar cross-section confirmed the examined ideas. That work allowed reconsidering the existed approaches and improving the scientific results significantly.

Nevertheless, distinguishing birds and insects remained a popular topic. Thus, Zrnic and Ryzhkov (1998) presented impressive results achieved with a 10cm pencil beam orthogonally polarized returns weather radar. They disclosed that the insects show a high degree of common alignment, and both reflectivity and differential reflectivity has a strong azimuthal dependence. Moreover, Doppler velocities indicated that insects primarily oriented either along or perpendicular to the wind direction.

Vertical-Looking Principle

Most of the earlier mentioned radar systems are scanning radar covering large areas (Riley, 1980). The vertical-looking radar is another solution, which often supplemented scanning systems and facilitates distinguishing insect species since it can provide higher-detail information (and, as a result, covers a much smaller area). In the 1990s, researchers applied vertical-looking radar widely for entomology purposes. In contrast to earlier established vertical-looking systems for entomology (Beerwinkle et al., 1995; Hobbs, 1991; Smith and Riley, 1996) introduced a novel solution, where the radar's beam nutates by a fraction of a beamwidth. At the same time, the plane of linear polarization rotates. That allows gathering the insects' speed and direction of motion, orientation, and three radar scattering cross-sections related to the insect body mass and shape.

Moreover, the discussed radar was connected to a computer; it was a large achievement. The discussed radar was a 3.2 cm wavelength device with a 1.5 m diameter paraboloid reflector and cylindrical metal shroud (30 cm high and lined on the inside with microwave absorbent material fitted to the rim of the paraboloid enabled to prevent the radar beam sidelobes from intercepting nearby elevated structures. Smith and Riley concluded that the utilized system was effective and explicitly mentioned the advantage of using the specialized software.

In the 2000s, researchers have continued to developed vertical-looking systems based on earlier achievements. Chapman et al. (2002) proposed a solution for estimating the body mass of insects, which allowed monitoring of the altitudinal and temporal dynamics of high-flying insect populations. That research aimed the long-term monitoring of aerial insects, which often comprises studies on the population dynamics of migratory insect species (Perry, 1993; Woiwod and Hanski, 1992), the impact of insect groups (Halbert et al., 1995; Fleming and Tatchell, 1995), and outbreaks of pest species (Tatchell,1991). Chapman et al. reminded that the great advantage of vertical-looking radar is the wobble (nutation) to the vertical beam allowing the mass estimation for over-flying targets, thus providing a powerful aid to identification. Their radar system emitted a circularly symmetric plane-polarized vertically directed beam nutating by 0.1 beam widths around its vertical axis. The plane of polarization was continuously rotated with the altitude range from 150 to 1188m above the system. The beam width was from 13m on the 150m altitude to 60m on the 1200m altitude; it could detect minimal targets from 1mg (low altitude targets) to 15mg (high altitude targets). As in the previous works (e.g., Smith and Riley (1996)), the researchers utilized the correlation coefficient (between recorded and simulated signals) and six parameters (i.e., the speed, direction, and orientation target trajectory parameters and a_0 , a_2 , and a_4 target radar scattering parameters). The following classification facilitated the target detection: "fail" targets excluding from further analysis for a signal failed to converge to a solution, "good" (correlation coefficient >0.9), "less good," and "poor" targets (correlation coefficient <0.7). The authors used various equations for the mass estimation; for instance, the target mass was estimated according to the following equation for small targets:

$$m=\left(\left(a_0-a_2+a_4\right)\cdot 10^5/6.4\right)^{0.5}$$

Moreover, that work showed many other empirical findings and dependencies.

Chapman et al. (2003) described a work conducted with a new vertical-looking radar system. The device had the linearly polarized and slightly oscillated (0.18offset around the vertical axis) beam. The beam continuously rotated by mechanically turning the upward-pointing wave-guide feed about the vertical. The radar proposed two outstanding solutions. First, it detected insects in several 50m-width altitude levels with 30m intervals in-between. Second, it delivered with autonomous data analysis software, which facilitated the individual target data calculation, including the size, shape, alignment, and displacement vectors allowing long-term monitoring of migrant insect populations. The complex software analyzed data using the six discussed earlier parameters plus the distance of the closest approach to the beam's central axis. These seven extracted parameters allowed producing a simulated signal and the correlation between this and the radar return; it provided a quantitative estimation of how well the model has described overflying targets. The authors processed only "good" targets. Even such data comprised rarely reflections from birds and bats, but some straightforward solutions filtered out them using masses and displacement speeds. As in previous works, the body shape of overflying insects utilized the maximum and minimum radar reflectivity denoted by σ_{xx} and σ_{yy} , respectively. For most insects in the UK, σ_{xx} corresponds to the situation when the plane of polarization is parallel to the insect's major body axis (length) and at minimum amplitude when it is parallel to its minor axis (width).

Moreover, Chapman et al. noticed that disparities of the $\sigma_{xx}:\sigma_{yy}$ ratio allow the insect shape estimation: large (e.g., "15:1") is for long thin bodies (e.g., Neuroptera), small (e.g., "5:1") is for more compact beetles, and "1:1" is for Coccinellidae. What is more, the signal modulation facilitated the investigation of orientation behavior (body alignment) and displacement direction. For the target's mass estimation, the authors defined the target's distance from the beam center using the nutation of the radar beam around the vertical axis. They also noticed that the wingbeat frequency could not be extracted in the nutation mode. Thus, the radar was operated for 5 minutes in the nutation model and 1 (following) minute in the non-nutation mode. Chapman et al. concluded that approximately 3 billion or one metric ton of overflying insects in one month in one month.

Furthermore, they proposed an advanced monitoring framework comprising temporal activity, insect layering, common orientation, and migration analysis approaches. In contrast to migrations observed with X-band radar Reynolds and Riley (1997), vertical-looking radar can only define a group of migrating insects' flight headings since it covers a small area. The heading is defined using the body orientation (alignment), displacement direction (however, the displacement direction is primarily determined by wind direction), and displacement speed of overflying migrants.

Harman and Drake (2004) published their approaches to vertical-looking radar (VLR); they called it "zenith-pointing linear-polarized conical-scan (ZLC) configuration." A synthesis paper by Hobbs and Aldhous (2006) summarized earlier harvested data (Riley, 1985; Aldhous, 1989). The discussion in the previous paragraph work did not consider the wingbeat. However, they concluded that it could be a good extension for the future. In 2004, Wang and Drake (2004) provided detailed results on this topic. They gathered wingbeat parameters using rotary-mode signals in a different, final stage of the data-processing procedure that routinely retrieves trajectory and target parameters from an IMR's conical-scan observations detailed in the previous work.

Harmonic Radar

All earlier discussed works belong to high-altitude flight observations (mainly using pulse radar). Unfortunately, those approaches do not work for low-altitude targets because of the ground clutter, excluding specific conditions (Loper et al., 1993). Mascanzoni and Wallin (1986) proposed promising solutions for this problem using the radar utilized for locating avalanche victims (Fuks, 1981). It was a harmonic radar system with a reflector (a tiny electronic diode glued to the insect). This diode can reflect microwave beams emitted by portable detection equipment. The proposed technique was effective in a field-trace experiment with carabid beetles. A diode re-radiates a harmonic frequency, i.e., original (or fundamental) wave frequency multiplied by a positive integer number Bingham (1994). In that experiment, Mascanzoni and Wallin used a 915 MHz radar system; the reflector produced a 1830MHz signal (i.e., a harmonic reflection with factor two). They tagged insects with reflectors; this break-through principle has not changed significantly since 1986.

Mascanzoni and Wallin glued a tag along with bodies; later, to improve flying insects' reflection, researchers started to use vertically glued tags. Riley et al. (1996) applied harmonic radar for tracking (bumble) bees' low-altitude flights in a distance range of hundred meters. In that works, the researchers successfully distinguished re-radiated harmonic signal and strong ground clutter. They investigated tree bumblebee (Bombus spp.) colonies and a small hive of honey bees (Apismellifera). Some regular forages were tagged and observed for several days. They successfully tracked those bees and proved that tagged been could forage. The authors noticed the height potential of harmonic radar for insects' low-altitude flights and admitted that more experiments are required to prove whether the tag significantly modifies insect behavior.

In the subsequent research, Riley and Smith Riley and Smith (2002) improved the design of their harmonic system. They noted that insects with weight more than ca. 50mg can wear an improved 1-12 mg tag. As in earlier works, a transponder (tag) re-radiated the frequency-doubled signals. However, the range was significantly increased up to 900m. Moreover, the new system allowed the authors to collect dynamic and geometrically correct records of the insects' horizontal flight trajectories by day and night.

Later, Colpitts, and Boiteau (2004) attempted to improve tags. They designed a tag with less than 3mg mass, achieving the most prominent possible return signal at the second harmonic frequency. They criticized the earlier works (Riley et al., 1996; Roland et al. 1996; Loevei et al. 1997; Reynolds and Riley 2002) for the lack of the description of expected performance and essential design parameters. What is more, they noticed the results of Riley and Smith (2002) indicated the minimal success of an earlier attempt and, instead, used empirical trimming to optimize performance. Colpitts, and Boiteau addressed the raised issues by providing the detailed description and performance evaluation of their transceiver verified with field experiments. They designed a dipole of length 12 mm with a 1 mm diameter loop that produced the most significant harmonic cross-section of 40 mm at the marine radar frequency of 9.41

GHz. They found that a dipole of 8 mm total length provided the maximum range when the feed point was located 2 mm from the insect.

Psychoudakis et al. (2008) proposed a principally new type of transponders. It was a modified Minkowski loop tag composed of two concentric fractal loops for a radar unit transmitting a 5.9–6 GHz signal and detecting at the 11.8–12 GHz band. The proposed planar geometry (bendable) tag design allowed improving harmonic conversion efficiency; it had a smaller size (9.5x9.5mm) than the earlier solutions and could detect a tagged insect up to 58 m. However, even though the transponder was designed for insects, in that works, the authors seemingly, did not test it with real insects and scheduled it for future work.

One can mention the lack of research on the tag impact on the insect flight. Kim et al. (2016) addressed this issue. They assessed the radar tag impact on five economically important insects. The authors utilized copper wire dipole radar tags described in (Boiteau et al., 2009; Lee et al. 2014): "the total length of the tag was 9mm with a 1mm-diameter loop at the pole, and a 1mm foot bent through 90". Kim et al. noticed the promising potential of the harmonic radar for three examined species; while, it showed a severe impact on two rest insects. The adhesive bond strength was assessed for this. The authors did not observe a significant correlation between bond strength and insect body size for all species. The radar tag attachment affected the flight behavior (including the takeoff) and capacity of five insect species in different ways.

Harmonic radar keeps attracting the height of attention of researchers proposing various novel solutions. For instance, Hsu et al. (2015) proposed to use a pseudorandom code principle in harmonic radar to achieve high sensitivity. Furthermore, advances in harmonic radar hardware and algorithms led to its "in-production" use for insect behavior investigation. For instance, in He et al. (2019), researchers tracked many Chinese citrus flies for several years. As a result, they disclosed that early emerged adult insects migrate into forests. Such works confirm the effectiveness of the technology.

Frequency Modulated Continuous Wave Radar

Most of the earlier mentioned works considered pulsed radar systems. As an alternative, frequency modulated continuous wave radar (FMCW) can be used for insect detection. FMCW radar is a popular technique for investigating layers in the atmosphere (Metcalf, 1975; Eaton et al., 1995; Dekker et al., 2002). Gallagher et al. (2004) detected meteorological echoes contaminated and obscured by echoes looking like the diurnal cycle of insect behavior. They noticed that the insects began to fly within an hour after sunset and reached a concentration peak near midnight. They found that insects show a robust diurnal cycle; insects are typically dormant during the day and active at night. The radar indicated that the insects started to fly after sunset, reached a peak near midnight with the following density decrease.

Of course, it was not the first attempt to use FMCW radar for insect detection. One of the earliest works was published in 1973 (Richter et al.). Richter et al. have mentioned that a housefly with a backscatter cross-section of 10-3cm2 for a radio wavelength of 10cm at a distance of 1 km produces echoes about 24db above the noise level. They carried out experiments with insects and steel balls and proved that the proposed technique is effective. Then a mobile radar worked for several days in a mild coastal climate area (San Diego) and desert area (Salton sea) to observe insects and atmospheric conditions. The radar antennas were fixed vertically. In the both areas radar registered clear echos from insects. They provided an attractive 3D chart showing the number of insect targets in time by altitude levels. What is more, the authors noticed the capability of the radar to "see" insects through clouds; insects were detected at altitudes up to 700 meters. Richter et al. concluded that FMCW radar could sense atmospheric conditions and insects simultaneously; they also pointed out the correlation between atmospheric conditions and insect behavior in both areas.

Contreras and Frasier (2007) provided the results of the S-band FMCW mobile radar exploitation during one month in Oklahoma. This design allowed the authors to reach an altitude of 2500m. As in work discussed in the previous paragraph, insects appeared as discrete dots in the resulting charts. Actually, as in many other works, the authors just assumed that these dot echos are insects ("assume to be insects").

Although they did not conduct experiments with artificially resided insects and other targets, their assumptions look convincingly since it corresponds to the independent finding in other works on insect radar. Furthermore, Contreras and Frasier proposed a two-dimensional (5x5) median filter to isolate the contribution from insects. That allowed distinguishing target types.

Noskov et al. (2021) suppose that FMCW systems can become the primary trending technology in the radar scope due to their compactness, energy effectiveness, and recent achievements in the data processing. They indicated that among recent advances in insect radar, FMCW approaches are outstanding and show high potential.

CONCLUSIONS

The present paper provides sufficient and compact information on radar and its applications aiming at the environment monitoring audience. It comprises the relevant references for obtaining all details regarding all described concepts. The author provided a standard and straightforward definition and brief history. Main radar components (i.e., the transmitter, target, receiver, and indicator) were introduced and illustrated through an intuitive life example. The example allowed formulating an equation of radar range. Then, the article discussed the material reflectivity and three relevant phenomena: noise, inference, and clutter. The radar range equation enabled us to provide a comprehensive overview of the major principles behind the technology. It introduced the "cross-section" term, an integral part of most works related to radar. In addition to the range measures, the present paper considered direction and seed measured. The latter comprises Doppler effect measures described in the article. It was shown that the velocity is defined using the Doppler shift (or the difference in the transmitting and receiving frequency). Researchers need to understand the significant types of radar systems. The relevant section showed that there are two main types: pulsed and continuous-wave sets. The modulation approach conducts further subdivisions. Additionally, radar systems can be monostatic, bistatic, search, and tracking radars. What is more, it is essential to understand the radar frequencies place at the electromagnetic spectrum. After the fundamentals, the paper discussed signal processing and application. It was emphasized that the radar cross-section and signal-to-noise ratio are the most critical components in signal processing. Since threshold-based processing is still the primary approach, it was discussed in detail. Finally, detection and false alarm probability were considered.

What is more, several techniques for detection probability improvement were considered. Then, the continuous wave signal processing was described with a particular focus on the ambiguity function and signal modulation.

Additionally, the author discussed the development of the radar aeroecology according to the main groups of radar approaches. The first group, pulsed scanning systems, has the most extended history and reached a well-established stage, allowing a large range mass target monitoring on a global scale. Vertical-looking principle of the second group allow higher granulated monitoring. Harmonic radar systems have long history and aim to track individual species. It was indicated that frequency modulated continuous wave radar set can soon play an important, if not a key, role in the radar aeroecology realm.

Advances in data processing, robotics, computation, and communications enable practitioners to combine the discussed radar solutions aiming at global avian and insect biodiversity monitoring and negative human impact systematic estimation. There is a need for global collaboration between aeroecological radar practitioners. First, since meteorological radar data comprise important aeroecological information and cover huge areas worldwide, these sources should be systematically archived and processed for aeroecological purposes mainly aiming at flying species and their habitat conditions. Second, acting insect and bird radar solutions should be continuously maintained for supporting the long term data series collection. Third, aeroecological radar networks should be developed at the global scope. Finally, cost effective compact FMCW radar devices running with autonomous sensor boxes or unmanned vehicles should attract a special attention for cutting-edge large scale aeroconservation and pest management.

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REFERENCES

Book with one author:

McKibben, B. (2003). *The End of Nature.*Bloomsbury Publishing, 2nd edition.

Samways, M. J. (2005). *Insect Diversity Conservation.*Cambridge University Press.

New, T. R. (2018). *Forests and Insect Conservation in Australia.*Springer International Publishing

New, T. R. (2009). *Insect Species Conservation.Ecology, Biodiversity and Conservation.*Cambridge University Press.

Parker, S. (2003).*McGraw-Hill Dictionary of Scientific and Technical Terms.*McGraw Hill Dictionary of Scientific and Technical Terms. McGraw-Hill Education

Rahman, H. (2019). *Fundamental Principles of Radar.*Taylor & Francis.

Watson, R. (2009). Radar *Origins Worldwide: History of Its Evolution in 13 Nations Through World War II.* Trafford Publishing.

Serway, R. A. and Vuille, C. (2017).*College physics.* Brooks Cole, eleven edition.

Hysell, D. (2018). *Antennas and Radar for Environmental Scientists and Engineers.*Cambridge University Press.

Book with two authors:

Author, A. A., & Author, B. B. (2005).*Title of work.*Publisher.

Budge, M. &German, S. (2015). *Basic Radar Analysis.Artech House radar series.*Artech House.

Book with more than two authors:

Groom, M., Meffe, G., and Carroll, C. (2012). *Principles of Conservation Biology*.Sinauer

Knott, E., Schaeffer, J., and Tulley, M. (2004).*Radar Cross Section.*Electromagnetics and Radar Series.Institution of Engineering and Technology.

Lothes, R. N., Szymanski, M. B., and Wiley, R. G. (1990).*Radar vulnerability to jamming. Norwood, MA*, Artech House, 1990

Richards, M., Melvin, W., Scheer, J., Scheer, J., and Holm, W. (2014).*Principles of Modern Radar: Radar Applications.*Electromagnetics and Radar.Institution of Engineering and Technology.

Journal article:

Lockwood, J. A. (1987). *The moral standing of insects and the ethics of extinction.* The Florida Entomologist, 70(1):70-89.

Hauser, C.E., Pople, A.R. and Possingham, H.P. (2006), *Should Managed Populations Be Monitored Every Year?* Ecological Applications, 16: 807-819.

Liu, Y., Cotton, J. A., Shen, B., Han, X., Rossiter, S. J., and Zhang, S. (2010).*Convergent sequence evolution between echolocating bats and dolphins.* Current Biology, 20(2):R53–R54.

Lonnqvist, A., Tamminen, A., Mallat, J., and Raisanen, A. (2006).*Monostatic reflectivity measurement of radar absorbing materials at 310 GHz.* IEEE Transactions on Microwave Theory and Techniques, 54(9):3486–3491.

Watts, S. (1987). *Radar detection prediction in k-distributed sea clutter and thermal noise.* IEEE Transactions on Aerospace and Electronic Systems, AES-23(1):40–45.

Galati, G., Pavan, G., and De Palo, F. (2017).*Chirp signals and noisy waveforms for solid-state surveillance radars.* Aerospace, 4(1):15.

Swerling, P. (1960). *Probability of detection for fluctuating targets.* IRE Transactions on Information Theory, 6(2):269-308.

Schwartz, M. (1956).*A coincidence procedure for signal detection.*IRE Transactions on Information Theory, 2(4):135-139.

Clement, M., Kilsby, C., and Moore, P. (2018).*Multi-temporal synthetic aperture radar flood mapping using change detection.* Journal of Flood Risk Management, 11(2):152--168.

Riley, J. R. (1985). *Radar cross section of insects.* Proceedings of the IEEE, 73(2):228—232

Riley, J. R., Reynolds, D. R., and Rainey, R. C. (1979).*Radar-based studies of the migratory flight of grasshoppers in the middle niger area of mali.*Proceedings of the Royal Society of London. Series B. Biological Sciences, 204(1154):67-82.

Mueller, E. A. and Larkin, R. P. (1985).*Insects observed using dual-polarization radar.* Journal of Atmospheric and Oceanic Technology, 2(1):49--54.

Drake, V. A., Helm, K. F., Readshaw, J. L., and Reid, D. G. (1981). Insect *migration across bass strait during spring: a radar study.* Bulletin of Entomological Research, 71(3):449-466.

Vaughn, C. R. (1985). *Birds and insects as radar targets: A review.* Proceedings of the IEEE, 73(2):205-227.

Zrnic, D. S. and Ryzhkov, A. V. (1998).*Observations of insects and birds with a polarimetric radar.* IEEE Transactions on Geoscience and Remote Sensing, 36(2):661-668.

Beerwinkle, K., Lopez Jr, J., Schleider, P., and Lingren, P. (1995).*Annual patterns of aerial insect densities at altitudes from 500 to 2400 meters in east-central texas indicated by continuously-operating vertically-oriented radar.*Southwestern entomologist. Supplement (USA).

Hobbs, S. (1991).*A radar signal processor for biological applications.* Measurement Science and Technology, 2(5):415.

Smith, A. and Riley, J. (1996).*Signal processing in a novel radar system for monitoring insect migration.* Computers and Electronics in Agricultu/re, 15(4):267–278.

Chapman, J., Smith, A., Woiwod, I., Reynolds, D., and Riley, J. (2002).*Development of vertical-looking radar technology for monitoring insect migration.* Computers and Electronics in Agriculture, 35(2-3):95–110.

Perry, J. N., Woiwod, I. P., and Hanski, I. (1993).*Using response-surface methodology to detect chaos in ecological time series.*Oikos, 68(2):329-339.

Woiwod, I. P. and Hanski, I. (1992).*Patterns of density dependence in moths and aphids.*Journal of Animal Ecology, 61(3):619-629.

Halbert, S., Jennings, M., Cogan, C., Quisenberry, S., and Johnson, J. (1995).*Potential use of suction trap collections of aphids as indicators of plant biodiversity.*Insects in a changing environment, 504.

Chapman, J. W., Reynolds, D. R., and Smith, A. D. (2003).*Vertical-Looking Radar: A New Tool for Monitoring High-Altitude Insect Migration.*BioScience, 53(5):503--511

Harman, I. and Drake, V. (2004).*Insect monitoring radar: analytical time-domain algorithm for retrieving trajectory and target parameters.* Computers and Electronics in Agriculture, 43(1):23–41.

Hobbs, S. and Aldhous, A. (2006).*Insect ventral radar cross-section polarisation dependence measurements for radar entomology.* IEE Proceedings - Radar, Sonar and Navigation, 153(6):502.

Wang, H. and Drake, V. (2004).*Insect monitoring radar: retrieval of wingbeat information from conical-scan observation data.* Computers and Electronics in Agriculture, 43(3):209–222.

Bingham, R. P. (1994). *Harmonics-understanding the facts.*Dranetz Technologies.

Loper, G. M., Wolf, W. W., and Taylor, O. R. (1993).*Radar detection of drones responding to honeybee queen pheromone.*Journal of Chemical Ecology, 19(9):1929–1938.

Mascanzoni, D. and Wallin, H. (1986). *The harmonic radar: a new method of tracing insects in the field.* Ecological Entomology, 11(4):387–390.

Fuks, P. (1981). *Harmonic radar, a modern method for location of avalanche victims.*Division of Electromagnetic Theory, Royal Inst. of Technology.

Riley, J. R., Smith, A. D., Reynolds, D. R., Edwards, A. S., Osborne, J. L., Williams, I. H., Carreck, N. L., and Poppy, G. M. (1996). *Tracking bees with harmonic radar.* Nature, 379(6560):29–30.

Riley, J. and Smith, A. (2002).*Design considerations for an harmonic radar to investigate the flight of insects at low altitude.* Computers and Electronics in Agriculture, 35(2-3):151–169.

Colpitts, B. and Boiteau, G. (2004).*Harmonic radar transceiver design: Miniature tags for insect tracking.* IEEE Transactions on Antennas and Propagation, 52(11):2825–2832.

Roland, J., McKinnon, G., Backhouse, C., and Taylor, P. D. (1996).*Even smaller radar tags on insects.* Nature, 381(6578):120–120.

Loevei, G. L., Stringer, I. A., Devine, C. D., and Cartellieri, M. (1997). *Harmonic radar - a method using inexpensive tags to study invertebrate movement on land.* New Zealand Journal of Ecology, 21(2):187--193.

Reynolds, D. and Riley, J. (2002).*Remote-sensing, telemetric and computer-based technologies for investigating insect movement: a survey of existing and potential techniques.* Computers and Electronics in Agriculture, 35(2):271-307.

Psychoudakis, D., Moulder, W., Chen, C., Zhu, H., and Volakis, J. L. (2008). *A portable low-power harmonic radar system and conformal tag for insect tracking.*IEEE Antennas and Wireless Propagation Letters, 7:444--447.

Kim, J., Jung, M., Kim, H. G., and Lee, D.-H. (2016). *Potential of harmonic radar system for use on five economically important insects: Radar tag attachment on insects and its impact on flight capacity.* Journal of Asia-Pacific Entomology, 19(2):371–375.

Boiteau, G., Meloche, F., Vincent, C., and Leskey, T. C. (2009).*Effectiveness of Glues Used for Harmonic Radar Tag Attachment and Impact on Survival and Behavior of Three Insect Pests.* Environmental Entomology, 38(1):168-175.

Lee, D.-H., Park, C.-G., Seo, B. Y., Boiteau, G., Vincent, C., and Leskey, T. C. (2014).*Detectability of halyomorphahalys (hemiptera: Pentatomidae) by portable harmonic radar in agricultural landscapes.* Florida Entomologist, 97(3):1131–1138.

Hsu, M.-L., Jan, S.-J., Tsai, Z.-M., Wang, H., Chang, F.-R., Jau, P.-H., Lin, K.-Y., and Yang, E.-C.(2015). *Portable 9.4/18.8 GHz harmonic radar system using pulse pseudorandom code principle.*2015 European Microwave Conference (EuMC)

He, Z.-Z., Luo, J., Gui, L.-Y., Hua, D.-K., Du, T.-H., Wang, F.-L., Liang, P., Shi, Y.-F., and Yang, X. (2019). *Tracking the movement trajectory of newly emerged adult chinese citrus flies with insect harmonic radar.* Journal of Asia-Pacific Entomology, 22(3):853–859.

Metcalf, J. I. (1975). *Microstructure of radar echo layers in the clear atmosphere.* Journal of the Atmospheric Sciences, 32(2):362--362.

Eaton, F. D., McLaughlin, S. A., and Hines, J. R. (1995).*A new frequency-modulated continuous wave radar for studying planetary boundary layer morphology.* Radio Science, 30(1):75--88.

Richter, J. H., Jensen, D. R., Noonkester, V. R., Kreasky, J. B., Stimmann, M. W., and Wolf, W. W. (1973). *Remote radar sensing: Atmospheric structure and insects.* Science, 180(4091):1176--1178.

Noskov A, Bendix J, Friess N. A Review of Insect Monitoring Approaches with Special Reference to Radar Techniques.Sensors. 2021; 21(4):1474.

A publication in a language other than English:

Perlya, Y. (1955). *How radiolocator works (Kakrabotaetradiolokator).* GosudarstvennoeIzdatelstvoOboronnoyPromyshlennosti, Moscow, USSR.

Edited book:

Richards, M., Melvin, W., Scheer, J., Scheer, J., and Holm, W. (2014).*Principles of Modern Radar: Radar Applications.*Electromagnetics and Radar.Institution of Engineering and Technology.

Chapter in an edited book:

McLean I.F.G., Key R.S. (2012) *A History of Invertebrate Conservation in the British Statutory Conservation Agencies.* In: New T. (eds) Insect Conservation: Past, Present and Prospects. Springer, Dordrecht.

Pyle R.M. (2012) *The Origins and History of Insect Conservation in the United States.* In: New T. (eds) Insect Conservation: Past, Present and Prospects. Springer, Dordrecht.

Watts C., Stringer I., Gibbs G. (2012) *Insect Conservation in New Zealand: An Historical Perspective*. In: New T. (eds) Insect Conservation: Past, Present and Prospects. Springer, Dordrecht.

Ishii M., Nakamura Y. (2012) *Development and Future of Insect Conservation in Japan.* In: New T. (eds) Insect Conservation: Past, Present and Prospects. Springer, Dordrecht

Taylor, J. D. (2016). *Introduction to advanced ultrawideband radar systems.*In Advanced Ultrawideband Radar, pages 19--36.CRC Press.

Taylor, J. D., Boryssenko, A., and Boryssenko, E. (2016).*Signals, targets, and advanced ultrawideband radar systems.* In Advanced Ultrawideband Radar, pages 83--122.CRC Press.

Anishchenko, L., Bechtel, T., Ivashov, S., Alekhin, M., Tataraidze, A., and Vasiliev, I. (2016).*Bioradiolocation as a technique for remote monitoring of vital signs.*In Advanced Ultrawideband Radar, pages 315--340. CRC Press

Riley, J. (1980). *Radar as an aid to the study of insect flight.* A Handbook on Biotelemetry and Radio Tracking, page 131–140.

Published proceedings:

Kostenko, A. A., Nosich, A. I., and Tishchenko, I. A. (2001).*Radar prehistory, soviet side: three-coordinate l-band pulse radar developed in ukraine in the late 30's.*In IEEE Antennas and Propagation Society International Symposium. 2001 Digest. Held in conjunction with: USNC/URSI National Radio Science Meeting (Cat.No.01CH37229), volume 4, pages 44--47 vol.4.

van Loon, B. (2005). *Radar 101: Celebrating 101 years of development.* Proceedings of the IEEE, 93(4):844–846.

Coca, E. and Cehan, V. (2014).*Laboratory study of electromagnetic waves reflectivity of certain materials.*Proceedings of the 2014 37th International Spring Seminar on Electronics Technology.

North, D. O. (1963).*An analysis of the factors which determine signal/noise discrimination in pulsed-carrier systems.* Proceedings of the IEEE, 51(7):1016-1027.

Hall, W. (1956).*Prediction of pulse radar performance.* Proceedings of the IRE, 44(2):224--231.

Rao, Y. S., Venkataraman, G., Rao, K. S., and Snehmani (2004).*Sar interferometry for dem generation and movemnet of indian glaciers.* In IGARSS 2004.2004 IEEE International Geoscience and Remote Sensing Symposium, volume 2, pages 1128-1131.

Fleming, R. and Tatchell, G. (1995).*Shifts in the flight periods of british aphids: a response to climate warming?*In: Insects in a changing environment, Royal Entomological Society of London,505-508

Tatchell, G. (1991). *Monitoring and forecasting aphid problems.* In Peters, D., Webster, J., and Chlouber, C., editors, Proceedings of the Conference on Aphid–Plant Interactions: Populations to Molecules., Experiment Station Miscellaneous Publication No. 132, pages 215 -- 231, Stillwater, Oklahoma. USDA – Agricultural Research Service and Oklahoma State University.

Dekker, P. L., Bajaj, A. N., and Frasier, S. (2002). *Radar and acoustic observations during vtmxfieldcampaign.*10thConference on Mountain Meteorology.

Gallagher, F., Bowers, J., Laufenberg, E., Jr, E., Storwold, D., and Mclaughlin, S. (2004). *Possible detection of insects in an urban environment by a frequency modulated-continuous wave radar.*5th Symposium on the Urban Environment, pages 347--353.

Contreras, R. F. and Frasier, S. J. (2007).*Return from insects in the clear-air convective boundary layer.* IEEE International Geoscience and Remote Sensing Symposium.

Unpublished doctoral dissertation or master's thesis:

USAAF (1945). *Graphic Survey of Radio and Radar Equip.* Used by the Army Air Forces [Sec. 1] Countermeasures Equipment, volume Section One. USAAF, 1 edition.

Aldhous, A. C. (1989). *An investigation of the polarisation dependence of insect radar cross sections at constant aspect.*PhD Thesis - Ecological Physics Research Group.

Website:

VandenBos, G., Knapp, S., & Doe, J. (2001).*Role of reference elements in the selection of resources by psychology undergraduates*.http://jbr.org/articles.html [Online; accessed 1-Oct-2021]

TutorialsPoint.*Radar Systems Tutorial*.https://www.tutorialspoint.com/radar_systems/radar_systems_tutorial.pdf. [Online; accessed 1-Oct-2021]

Wolff, C. (2009a). *Radar tutorial.* http://www.radartutorial.eu/druck/Book1.pdf.[Online; accessed 1-Oct-2021].

Wolff, C. (2009b). *Radartutorial: Book 2 - radar sets.* http://www.radartutorial.eu/druck/Book2.pdf. [Online; accessed 1-Oct-2021].

Wolff, C. (2016). *Radartutorial: Book 7 - intrapulse modulation.* http://www.radartutorial.eu/druck/Book7.pdf.Online; accessed 1-Oct-2021].

KEY TERMS AND DEFINITIONS

Aeroecology:a discipline aiming at airborne life forms and their interactions with the environment.

Pulsed Radar:a radar system that determines the range to a target using pulse-timing techniques.

Vertical-LookingRadar:a sky-oriented radar system gathering fine-grain information about flying species (i.e., body orientation, wingbeat, heading). It often utilizes pulsed radar sets.

Harmonic Radar:a radar principle in which the second or third harmonic of a transmitted radar frequency is detected

Frequency Modulated Continuous Wave Radar (FMCW):a radar system radiating continuous transmission power and changing its operating frequency during the measurement.