Electronic Combat in Nature

ABSTRACT

This article examines radar and electronic warfare in nature. It briefly defines electronic warfare and investigates how some animals use electronic combat techniques for hunting and evasion. In particular, it delves into the electronic weapons of bats and moths. It describes how the bat uses different radar and electronic warfare techniques to locate its prey and for manoeuvring - pulse frequency repetition agility, frequency modulation, Doppler, multimode and monopulse operation, tracking and even pulse integration and processing. It also explains how the moth combats this through its radar-warning receiver or through hiding in clutter to deceive or evade the bat. To counteract this, the bat further develops its electronic countermeasures. Finally it puts forward a case on how such knowledge can help to address some of the military problems in radar and electronic warfare.

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INTRODUCTION

"A flying object homes in on its target. Flying in darkness, it finds its target by sending out streams of short pulses. But the target does not give in so easily. It detects the homing pulses and dodges evasively to avoid attack. Sometimes, it counter attacks with blasts of pulses of its own to confuse and disorientate the attacker."

Is this a picture of modern aerial and electronic warfare? Yes, but it is warfare in nature between bats and their prey, the moths. Bats use a form of sonar known as echolocation to locate their prey. To accomplish this, bats emit very high frequency sounds that bounce off moths and other insects, giving them an estimate of the prey's relative location. Bats have developed a technique to filter out the most powerful sounds so that they can concentrate on the faint return signals. Moths have in turn evolved a defence in the form of a soft covering on their bodies and wings, which absorbs the bat chirps. In response, bats have evolved new chirp frequencies that can be used to identify the moths' fuzzy coating. To counter this, the moths have enhanced their stealth technology with a jamming technique that involves emitting their own sounds to jam the bats' return signals. This is often coordinated with elaborate evasive manoeuvres. Bats respond by adopting an elaborate flight pattern that can overwhelm a moth's senses, and also by periodically turning off their echolocation, making the moth's jamming technique less effective. Nature's electronic warfare arms race continues...

In this article, the author examines radar and electronic warfare in nature. The first part defines radar and electronic warfare and looks at how some animals use electronic combat techniques for hunting and evasion. The second part delves into the electronic weapons of the bat and moth, and shows how they can help to address some of the military issues in radar and electronic warfare. A glossary of biological, radar and electronic warfare terms can be found at the end of the article.

WHAT IS RADAR AND ELECTRONIC WARFARE?

Radar is an electromagnetic system for the detection and location of objects. It operates by transmitting a particular type of waveform and detecting the nature of the echo signal. It is designed to `see' in conditions unfriendly to normal human vision. These include darkness, haze, fog, rain or snow. Moreover, it can measure the distance or range to the object. Echolocation is a system of orientation or radar involving the use of echoes produced by the animal for gathering information about the environment.

Electronic warfare is a military action where the objective is to control the electromagnetic spectrum (Schleher, 1999). To accomplish this, both offensive electronic attack (electronic countermeasure) and defensive electronic protection (electronic counter-countermeasure) are required. In addition, electronic warfare support (electronic support measure) actions are necessary to supply the intelligence and threat recognition that allow implementation of both electronic attack and protection.

NATURE'S ELECTRONIC WEAPONS

Although there is no known animal species that uses electromagnetic waves at radio frequencies or microwaves, examples of animals using sound, light and electric field for electronic combat abound. The ultrasonic sensor of a bat is the "mother of all radars" used for navigation, surveillance and hunting food. Apart from bats, there are other creatures that use acoustic echolocation. Dolphins have highly sophisticated sonars that are not yet fully understood by humans. There are echolocating birds too: the oilbird and the White-rumped Swiftlet or the Black-nest Swiftlet (Bossel, 2001a). To combat the bat's echolocation, moths have developed ears that can detect bats' signals and trigger a series of clicking noises that jam the bat's detector (self-protection jammers). Some electric fishes create an electric field around themselves, which is used to detect and communicate with other fish. They have even adopted frequency hopping where they hop from one frequency to another to avoid jamming.

In the depths of the ocean are the habitats of some real electronic warfare experts (Bossel, 2001b). The Hatchet Fish takes advantage of the low illumination by looking upwards and waiting for the shadow of some other animal swimming by. Through evolution, prey animals have found stealth to be a countermeasure. Some fish and cephalopods exhibit bioluminescence where their skin is able to emit just about the right amount of light to compensate for their own shadow and thus render themselves undetectable. One notable example is the squid. Other animals have developed chromatophores. They can adapt the colours and texture of their skin such that it matches the structure of their hiding place. An example of such animals is the octopus. Some species, like the cuttlefish, produce sticky and luminescent mucus when put under stress by an attacker. This slime adheres to the predator and makes it a distinguishable target for predators further up the food chain (target illumination). The anglerfish features a luminescent appendix to its lower chin. This appendix is used as bait (decoy) for other predators while the anglerfish is lying in ambush. Glass worms produce a sort of liquid that contains hundreds and thousands of luminescent particles when pursued by a predator. In similar fashion, the jellyfish is able to jettison some of its twinkling tentacles and escape, mostly unharmed. These particles serve to confuse the predator's senses, just like chaff that is jettisoned from modern aircraft to confuse a hostile radar or missile seeker head.

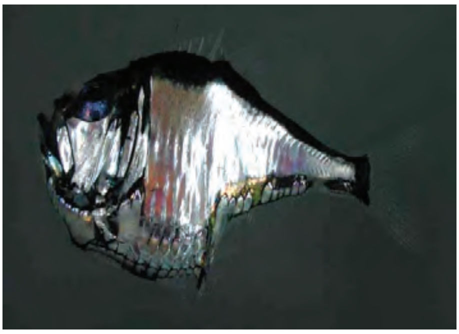

Figure 1. Hatchet Fish

BATS' ELECTRONIC WEAPONS

Contrary to popular belief, bats can see fairly well. However, their eyes are useful sensors only under daylight conditions and they only hunt in the dark. To support their night activities, bats have developed an active acoustic sensor in the ultrasonic frequency range. Apart from differences in frequencies and the wave medium between acoustical waves and radio waves, a bat's sensor is very similar to radar: chirped signal, target tracking by Doppler estimation, terrain avoidance function, and fine angle measurement based on the monopulse principle.

Bats' echolocation sensors are used for navigation, obstacle avoidance and hunting. Occasionally, they emit a short cry that serves to 'illuminate' the scene ahead. Echoes are picked up by their ears and analysed in the brain. The time between sending out a cry and receiving a response enables the bat to determine the distance between the bat and whatever objects that happen to be around. Stationary objects yield an echo that is a replica of the pulse sent. Moving objects are revealed by an echo at a slightly lower or higher frequency because of Doppler estimation (Moving Target Indicator (MTI). Furthermore, echoes from mosquitoes, moths and butterflies exhibit fluctuations that are caused by the flutter of their wings, a concept similar to unintentional modulation on pulse. This enables bats to tell the difference between a moth and a leaf swaying in the wind. Some bats feed on fish rather than on insects. These bats can detect the perturbations on the water surface when a fish is close to it. This enables them to find their submerged prey.

Bats begin their pursuit of prey while in the search mode, emitting pulses with long duration and inter-pulse intervals. Once they have detected a potential prey, they decrease their pulse duration, shorten the time interval between pulses and change the intensities of the pulses as they proceed from the search phase to the capture of the target through the approach, track and terminal phases of the echolocation attack sequence.

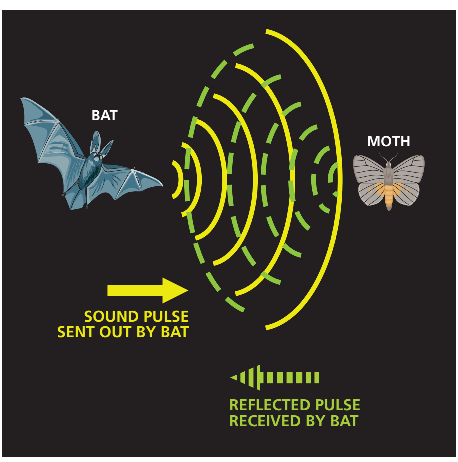

Figure 2. Echolocation

Waveforms

All bats use pulses called 'clicks'. In the search mode, bats operate in the Low Pulse Repetition Frequency (PRF) range. They would not emit a pulse before the last possible echo from the previous pulse has arrived and thus their range measurements are unambiguous. Within their pulses, bats use a variety of waveforms that are adapted for their very special purposes. These are classified as Constant Frequency (CF), Frequency Modulated (FM) or CF-FM.

Constant Frequency

These are narrowband sounds of milliseconds duration and transmitted without significantly changing the frequency. They are good for detection because there is a lot of power within a single channel. However these signals are poor for localisation or direction finding because they provide neither good monaural nor acceptable binaural cues. Thus they have poor range resolution and do not yield detailed information though they can determine Doppler shifts. They give information on the approach and departure of the target and rates of change. CF bats usually hunt in open terrain where anything that appears in the air can be considered food. Some CF bats do not loiter above an area but hang off a tree, scanning the area for anything that moves. CF bats operate at lower ultrasonic frequencies (around 30kHz) that suffer less attenuation in the atmosphere than higher frequencies and therefore yield more detection range. The downside is that low frequencies equate to large wavelengths (1.13cm at 30kHz), which yield strong echoes only from bigger insects.

If the CF pulse is long enough, echo fluctuations caused by wing flutter can be detected as well. Therefore, long CF pulses are also suitable for hunting within a background of stationary returns from vegetation (clutter). This signal type is employed at higher frequencies (60kHz and more) which produce stronger echoes from small insects and do not require big ears for sufficient precision in direction finding.

The Saccopteryx bat uses short CF pulses, but successive pulses alternate between two different frequencies, with the separation between them being equal to the Doppler shift that would be produced due to the flight speed of the bat (MacÍas, Silvio, Mora and Emanuel, 2003). It has been suggested that the bat may be using one of the tones as an uncompensated "ground-looking" sonar for

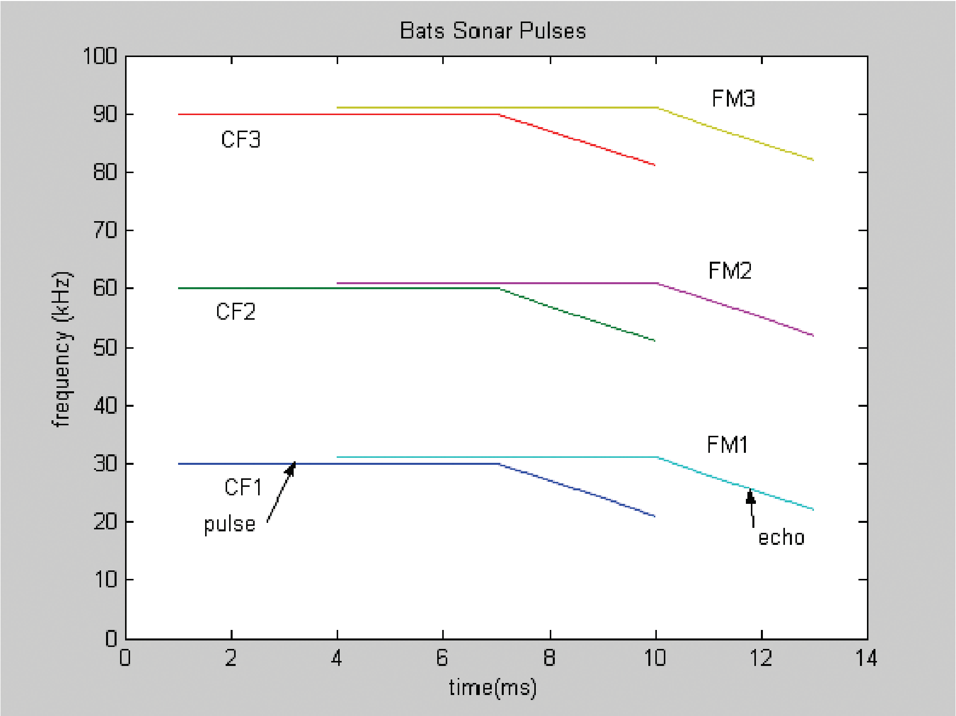

Figure 3. Use of CF and FM pulses and harmonics in bats

navigational purposes while the other may be pre-compensated for the bat's flight speed as a forward looking hunting system.

Frequency Modulation

These are broadband sounds. They are poor for detection since each auditory channel receives only a small time slice of the echo and thus will be weak. However, they are good for localisation or direction finding. Each auditory channel receives an echo for only a short time. Therefore, the temporal marking of the echoes is easy to compute. Since many channels are activated, the auditory system can combine signals across channels to get intensity and timing differences. The frequency changes within the pulse in all known cases vary from high to low (though the reason why the "down" chirp and not the "up" chirp is used is still unknown). The FM signal closely resembles a radar's chirp signal and lends itself well to range finding. Furthermore, it yields a spectral signature that is useful for determination of an object's size, shape and surface detail and discrimination between object types. Some bats have developed non-linear frequency modulation too.

Constant Frequency - Frequency Modulation

This denotes a combination of CF and FM. The pulse consists of a constant frequency portion to which a chirp is attached. This is a complex signal which combines the capabilities of both its components because the CF part yields good detection properties and the FM part provides the range information (See Figure 3). This signal is advantageous in dense vegetation where it is necessary to be able to classify an object into stationary; moving and not edible; and moving and edible.

CF-FM bats can switch between waveforms. Examples are the European Pipistrelle and the Moustached Bat, which employ CF and FM type waveforms during a single engagement (Suga, Simmons and Jen, 1975). Greater Horseshoe Bats use CF pulses when looking for prey in a stationary position but switch to a CF-FM signal once they are tracking a target.

All bats transmit overtones (or harmonics) too. Overtones serve to increase the bandwidth of the signal, which yields more detailed information (e.g. CF2 is a harmonic of CF1 in Figure 3). Harmonics are especially useful in cluttered situations. However, since higher frequencies or harmonics are subjected to stronger attenuation in the air, they are only suitable for use at the terminal phase of hunting.

Receiver

A bat's cry is so loud that the animal would instantly deafen itself if the cry is permitted to enter its own hearing apparatus. A bat's middle ear is built like a regular vertebrate's ears: there is the tympanic membrane which collects sound waves and converts them into mechanical oscillations; these are transferred to the oval window via the movements of the ossicles. There is however a subtle but important difference: some bats feature an additional muscle that disengages the ossicles or attenuates their movements when a cry is produced. Thus, the bat can literally switch off its receiver chain whilst transmitting a pulse. This muscle is precisely what a transmit/receive switch or duplexer is to man-made radar.

Bats hear sounds through their ears, which direct the sound through the inner ear and onto the basilar membrane of the cochlea. The basilar membrane in turn vibrates according to the frequency of the sound and turns that mechanical signal into a neural code that is carried into the brain stem and to the rest of the brain. The bat is not only getting information from its fundamental frequency, but also from the second, third and fourth harmonic frequencies of that pulse. The Moustached Bat's basilar membrane is thickened precisely at frequencies of 61kHz - 61.5kHz (Kruse, 1996). These frequencies correspond to the returning echoes of the Doppler shift compensated second harmonic of the CF-FM pulse. The bat lowers its own emitted CF so that the Doppler-shifted echo returning from the insect is precisely in the range where the bat has the best chance of detecting it: 61kHz - 61.5kHz. This area has neurons that are sensitive to a particular frequency and amplitude that will excite them maximally and is used in discriminating minute differences in frequency that would cause a flying insect to appear above the background noise and existing Doppler shift. Another area of interest that also relates to the bat's use of Doppler shift information is the CF area of the auditory cortex. This is the area in the cortex where the bat calculates the actual Doppler shift from the target. The bat does this by comparing the frequencies between the CF pulse and its second and third harmonic echo.

The problem of interference from the signals of other bats is significant for both CF and FM bats. The FM bat can average the echoes it receives over several pulses (integration of pulses); the image due to his own signals will be stable while interfering signals will be incoherent and will therefore just contribute to background noise. Targets with changing range can be allowed for by predicting their new expected position extrapolated from previous range measurements as long as the acceleration is not too great (tracking). The task is made easier by the fact that the bat has an extremely good spatial memory, on which he will often rely in preference to contradictory echolocation information, so that the static background environment will provide a constant reference system.

Technical Data

A data sheet of a bat's electronic weaponry could be as follows:

Frequency Range
Bat cries are from 12kHz to 200kHz.

Pulse Width
A single cry can be from 0.3ms to 200ms.

Navigation and Obstacle Avoidance
Bats can avoid wires as thin as 0.3mm in diameter.

Detection Range
Bats can detect moths 5m away on average. There are some bats that can detect fruit flies from 30m away.

Doppler Resolution
Bats can resolve constant frequency shifts of 0.1% caused by the Doppler effect. At a frequency of 83kHz, horseshoe bats can detect echo fluctuations at a rate of 30Hz caused by the wing flutter of an insect. A ratio of 30 to 83000 is less than 0.04%.

Range Resolution
Bats can resolve echoes received 80 microseconds apart. This translates into the capability to perceive two objects as two objects if they are located at least 27mm away from each other.

Scan Rate
Bats are able to process 200 air picture updates per second.

Engagements Per Hour
Bats can engage 1200 mosquitoes an hour or one mosquito every three seconds.

Multi-Mode
The sensor of the European Pipistrelle bat is a multi-mode device (Bossel, 2001a). The Pipistrelle employs a long continuous wave pulse for acquisition of moving targets and switches over to a chirped signal once it has begun pursuit of its prey. Translated into electronic combat terms, this means that the Pipistrelle features a target acquisition mode and a target-tracking mode.

Figure 4. The European Pipistrelle

PRF Agility
Bats emit 5 - 20 pulses per second in navigation mode. Thus, their PRF is 5Hz - 20Hz, which yields unambiguous ranges between 8.5m and 34m (unambiguous range = speed of sound / (2 x PRF)). However, the PRF does not remain fixed but is adapted to the situation. If there is something interesting, the PRF is increased for what could be called 'track confirmation'. This means more pulses are sent out at around 50Hz to get more information about a possible target. But during the whole engagement, bats keep their PRF such that range measurement remains unambiguous. Before capturing their prey, CF-FM bats increase their PRF up to 100Hz (unambiguous up to 1.7m) and FM bats can go up to 200Hz (unambiguous up to 0.85m). Increasing the PRF also means that the pulse duration is also reduced, yielding better range measurements.

Monopulse
Bats have two ears and they use them to compare results like two antennas. Thus, it is possible to achieve very precise angular information even if the antennas - taken individually - have rather large beamwidths. This technique is called simultaneous lobing or monopulse. Bats use this comparison technique in the horizontal plane.

Doppler Tracking
Doppler tracking, or Doppler shift compensation is not performed when a target is receding and its echo appears below the bats' hearing range. This indicates that the bats are not interested in anything that flies faster than them, as they cannot catch these prey anyway. At the same time, Doppler shift compensation ensures that transmitted signal is kept outside the sensitive frequency range. Thus, CF bats use the same method for transmitter/receiver isolation as employed in continuous wave radars.

MOTH'S ELECTRONIC WEAPONS

Tiger moths, including the garden tiger moth and the dogbane tiger moth are part of bats' diet. Millions of years of evolution have caused the moth to develop a warning device and a jammer (Fullard, Simmons, Saillant, 1994) to counter its predator.

The warning device of a tiger moth is a pair of ears on the head which are tuned to the frequency range used by their predators. Other moths developed ears on the body, wings and mouth-parts. Like any radar-warning device, the moth takes advantage of the $1/r^2$ law: signal strength decays at a rate inversely proportionate to the distance, squared. The bat's cry undergoes this attenuation once on the way out, and an echo undergoes it a second time on its way back. Therefore, the moth is able to detect the bat from some 40m away while the bat can hear the echo only at 5m. Upon detection of a bat's target acquisition signal, the moth takes immediate evasive action by hiding or quickly getting away. If the bat is too near, the moth flies in loops, makes surprising noises (jamming) or folds up its wings and power-dives to the ground.

A tiger moth's jamming signal consists of a series of false echoes whose purpose is to get rid of the bat. The sound is made by rubbing a leg or vibrating castanet-like structures on the wings (Metzner, 1999). Some theories about the working mechanism are:

Deception

The false echoes lead to confusion, processor overload and the impression of being outnumbered. Experiments have shown that bats ignore the majority of false echoes but their range measurement circuitry is severely hampered by pulses that appear 1ms - 2ms before the real one.

Competition

The false echoes convey the information that there is another bat already engaging the target.

Warning

The moth gives clear notice that it tastes so awful that the bat had better look for something else to feed on. Tiger moths feed on toxic plants that give them an unpleasant taste.

Surprise

These sounds simply surprise the bats and give the moths a little more time to escape.

Moths have also developed fuzzy wings that do not reflect the bat's pulses (stealth).

Some moths do not have ultrasound hearing organs (Waters and Jones, 2001). Moreover, they also seem to lack other predator defences

Characteristic	Airborne Radar	Bat's Sensor
Frequency Range	Usually above 8GHz	12kHz to 200kHz
Pulse Width	Microseconds	Milliseconds
Navigation and Obstacle Avoidance	Yes	Can avoid wires as thin as 0.3mm in diameter.
Detection Range	500m – 600km	5m – 30m
Range Resolution	100m	30mm
Multi-Mode	Search and track	Search and track
PRF Agility	Low PRF of 250Hz Medium PRF of 15KHz High PRF of 300KHz	Low PRF of 5 to 20Hz, Medium PRF of 50Hz. High PRF of 200Hz
Monopulse	Yes	Yes
Doppler Tracking	Yes	Yes

Table 1: Comparison between a typical airborne radar and a bat's sensor.

such as warning colouration, erratic flight patterns or good flight manoeuvrability. Despite this apparent lack of defences against predators, the species survived. They do so by choosing a very limited time to fly (radio silence), being conspicuous for just two weeks in summer for just half an hour around dusk where the males try to attract the females. They also hide in the grass, staying above the grass leaves so that they are still visible to the females, but concealed in the acoustic clutter.

ELECTRONIC COUNTER COUNTERMEASURES

To avoid being detected by some clever moths, bats have invented passive location too! The long-eared bat carries its name because of its really big ears. They are so sensitive that the bat can detect the tiny noises of the pre-flight warm-up cycle of some insects – without transmitting anything. These whispering bats produce extremely soft sounds so that they can still echolocate but the moths cannot quite hear them (Siemers, Stilz, and Schnitzler, 2001). Bats also emit calls that are too short in duration to be reliably encoded by the moth's most sensitive auditory receptor. The echolocation of gleaning insectivorous bats are acoustically mismatched to the ears of moths and are consequently less detectable than those of acoustically hawking bats. These bats use cries of short duration, high frequency and low intensity. Some bats develop a different type of pulse that can pick up fuzzy-winged moths. Other bats use frequencies above and below the insects' hearing range; or confuse the insect's locator by flying erratically. Others like the fringe-lipped bat or Central America's frog-eating bat have specialised in homing in on the mating calls that some frogs produce (Cramer, Michael, Willig, Michael, Jones and Clyde, 2001).

MILITARY APPLICATIONS

The appreciation of how bats operate in their natural environment could produce better sonar navigation and detection equipment and radar systems. Many of the principles that can be learned from the bat's sensor have already become part of the radar vocabulary. These include the use of multimode and monopulse radars, PRF agility and Doppler tracking. Table 1 shows a comparison of a typical airborne radar and a bat's sensor. They have many similar functions and characteristics. A study on how bats or birds catch fish may lead to new ideas for the detection of submarines - from the example where bats detect ripples in water to catch fish under the water. The use of channelised receivers coupled with neural network signal processing such as those used by bats could certainly improve the performance of electronic support receivers. By studying how bats detect minute changes in frequencies, better receivers could be built. The fuzzy materials of moths could be used to make stealth materials and their deception jamming methods could be used in electronic attack.

CONCLUSION

Bats and moths are continuously waging war with electronic weapons of sound that were developed millions of years ago (whereas the modern radar was discovered only in the 1930s) and are still evolving. Similarly, electronic warfare is an endless game of countermeasures and counter-countermeasures. Nature has provided many examples of electronic combat. Hopefully, an insight into the tactics, principles and materials used in nature could inspire new applications and improvements in electronic warfare.

GLOSSARY OF BIOLOGICAL, ELECTRONIC WARFARE AND RADAR TERMS

Biological Terms

BASILAR MEMBRANE: cellular membrane in which the hair cells are embedded. The basilar membrane moves in response to pressure waves in the cochlea, initiating a chain of events that result in a nerve impulse travelling to the brain.

CEPHALOPODS: class of the molluscs or soft-bodied animals, characterised by having the mouth surrounded by a greater or lesser number of fleshy arms or tentacles, which, in most living species, are furnished with sucking-cup (example: cuttle-fish).

CHROMATOPHORES: special skin cells that change a chameleon's colour.

COCHLEA: the coiled organ in the inner ear that converts mechanical energy (vibrations) and sorts them by frequency into nerve impulses that are sent to the brain.

OSSICLES: three tiny bones in the middle ear.

TYMPANIC MEMBRANE: a thin membrane in the middle ear that carries sound vibrations to the inner ear.

Electronic Warfare and Radar Terms

CHAFF: ribbon-like pieces of metallic materials which are dispensed by aircraft to mask or screen other aircraft or to cause a tracking radar to break its lock.

CHIRP: a repetitive and continuous change of carrier frequency of a pulse-modulated wave. Generally for the purpose of coding or pulse compression.

CLUTTER: the presence of reflections (echoes) from objects in the area of the target.

CONTINUOUS WAVE: continuous flow of electromagnetic energy (non-pulsed).

DECOY: a device used to improve aircraft survivability by delaying or denying acquisition of the real target.

DETECTION: acquisition of an electromagnetic signal with the same output characteristics as the original transmitted data.

DIRECTION FINDING: refers to the establishment of the direction from which a received signal was transmitted.

DOPPLER (EFFECT): measures the shift in frequency created when an object (being "illuminated" by energy waves) moves. A transmitter emits energy at a specific frequency which, when reflected, can indicate both speed and direction of that target.

DUPLEXER: device used to perform the switch over between transmitter and receiver ports when they share the same antenna.

ECHO: in radar, that portion of energy reflected from the target to the receiver.

ELECTRONIC WARFARE: a general term used to describe the use of communications systems in warfare. As such, electronic warfare includes the Electronic Order of Battle (EOB), reconnaissance, intentional interference, intrusion or intelligence collection.

ELECTRONIC ATTACK / ELECTRONIC COUNTERMEASURES: the intentional use of electronics equipment for the purpose of interference, or confusion in order to obtain a tactical advantage in support of a larger operation.

ELECTRONIC PROTECTION / ELECTRONIC COUNTER-COUNTERMEASURES: the design or redesign of equipment to make a communication system or equipment techniques less vulnerable to a known or projected electronic countermeasure equipment.

FALSE ECHOES: radiated bundle of electromagnetic energy which is displaced in time from the real target echo which creates a response in the receiver where no reflecting surface exists.

FREQUENCY AGILITY: the rapid and continual shifting of a transmitter's mean frequency, generally to avoid jamming.

FREQUENCY HOPPING: an anti-jamming technique used by a radar system. The carrier frequency of the pulsed transmissions are periodically or continuously shifted within limits on each successive pulse.

FREQUENCY MODULATION (FM): the modulation of a sine wave carrier so that its instantaneous frequency differs from that carrier by the amount proportional to the amplitude of the modulating wave.

INTEGRATION OF PULSES: estimation of signal parameters from a sequence of pulses in a radar.

UNINTENTIONAL MODULATION ON PULSE (UMOP) - Unintentional frequency variations of a transmitter caused by non-linearities, non-ideal transmitter tubes, modulators, high voltage components, etc. and is an inherent characteristic of high-powered transmitters, exploited by electronic support measures for emitter identification.

JAMMER: a device used to deprive, limit or degrade the use of a communications system. Radio frequency jammers include barrage, noise, discrete frequency repeater and deceptive equipment.

JAMMING: the intentional interference between two communications systems whereby one system attempts to degrade or make the second system useless.

MAXIMUM UNAMBIGUOUS RANGE: the maximum range beyond which targets appear as second-time-around echoes.

MONOPULSE: radar which is capable of obtaining highly accurate directional information by employing a receiving system with two or more overlapping lobes in the radiation patterns.

MTI (MOVING TARGET INDICATOR): a pulse radar which observes the unambiguous range condition while utilising Doppler effects (not Doppler) for ambiguous frequency resolution.

NOISE: any unwanted electrical or mechanical disturbance which modifies the desired performance.

PASSIVE: an inert component which may control, but does not create or amplify information for the purpose of jamming.

PULSE REPETITION FREQUENCY: frequency at which a pulse of certain width and amplitude is repeated.

RADAR: an acronym for Radio Detection and Ranging. It is used to detect a distant target, determine and display its relative direction (azimuth) and determine and display its relative distance (range).

RADAR WARNING RECEIVER: device for monitoring the direction and type of potentially hostile systems relative to the observing platform.

RANGE RESOLUTION: the ability of radar to discriminate two targets closely located in range.

STEALTH: use of special radar absorbent materials, flat angular surface design and other techniques to minimise the amount of radiation reflected to a radar installation, causing an aircraft or other vehicle to appear as a much smaller signal or not at all.

TRACKING: the continuous monitoring of range, velocity and position of a target in space from a reference position.

REFERENCES

Arlettaz, R., Jones, G., and Racey, P. A. (2001) Effect of Acoustic Clutter on Prey Detection by Bats. Nature, Vol. 414, December 2001, pp 742-745.

Bossel, S. (2001a) How a Bat's Sensor Works. BBC, http://www.bbc.co.uk/dna/h2g2/A748749.

Bossel, S. (2001b) Electronic Combat in Wildlife. BBC, http://www.bbc.co.uk/dna/h2g2/A729551.

Cramer, Michael J., Willig, Michael R., Jones, Clyde (2001) Trachops Cirrhosus. Mammalian Species Vol. 656, Issue 1, pp 1-6.

Faure P. A., Fullard, J. H. and Dawson, J. W. (1993), The Gleaning Attacks of the Northern Long-Eared Bat, Myotis Septentrionalis, are Relatively Inaudible to Moths. The Journal of Experimental Biology, Vol. 178, Issue 4, pp 173-189.

Fullard, J. H., Simmons J. A. and Saillant, P. A. (1994) Jamming Bat Echolocation: The Dogbane Tiger Moth Cycnia Tenera Times its Clicks to the Terminal Attack Calls of the Big Brown Bat Eptesicus Fuscus. The Journal of Experimental Biology, Vol. 194, pp 285-298.

Griffin, D.R., Webseter F.A., Michael, C.R. (1960), The Echolocation of Flying Insects by Bats. Animal Behavior, Vol. 8, pp 151-154.

Kruse, A. (1996), Echolocation in the Bat. Model System in Neuroethology, December 1996.

MacÍas, Silvio, Mora, Emanuel C. (2003) Variation Of Echolocation Calls Of Pteronotus Quadridens (Chiroptera: Mormoopidae) In Cuba. Journal of Mammalogy, Vol. 84 Issue 4, pp 1428-1436.

Metzner, J. (1999) Tiger Moths: Arms Race. http://www.pulseplanet.com/archive/Jul00/1929.html.

Schleher, D.C. (1999) Electronic Warfare in the Information Age, Artech House.

Schulze, W. and Schul, J., (2001) Ultrasound Avoidance Behaviour in the Bushcricket Tettigonia Viridissima. The Journal of Experimental Biology, Vol. 204, Issue 4, pp 733-740.

Siemers, B. M., Stilz, P. and Schnitzler, H. (2001) The Acoustic Advantage of Hunting at Low Heights Above Water: Behavioural Experiments on the European Trawling Bats Myotis Capaccinii, M. Dasycneme and M. Daubentonii. The Journal of Experimental Biology, Vol. 204, pp 3843-3854.

Simmons, J.A. (1979) Perception of Echo Phase in Bat Sonar. Science, Vol. 204, pp 1336-1338.

Suga, N., Simmons, J. A., Jen, P. S. (1975) Peripheral Specialisation for Fine Analysis of Doppler Shifted Echoes in the Auditory System of the CF-FM Bat Peteronotus Parnellii. Journal of Experimental Biology, Vol. 63, pp 161-192.

Waters, D. and Jones, G. (2001), The Peripheral Auditory Characteristics of Noctuid Moths: Responses to the Search-Phase Echolocation calls of Bats. The Journal of Experimental Biology, Vol. 199, Issue 4, pp 847-856.

Wesson, R. (1991) Beyond Natural Selection. Cambridge, Mass: Bradford Books/MIT Press.

BIOGRAPHY

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