Hornet Biological Radar for Detection, Tracking, Direction Finding, and Long Distance Communication: Is This Possible?

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Abstract

The late, great entomologist, Prof. Jacob S. Ishay, from the faculty of medicine in Tel-Aviv University, dedicated his life to hornet research. He found that the hornet's body produces a considerable amount of electrical energy by means of photovoltaic and piezoelectric effects. Using an electronic microscope, Prof. Ishay showed to the authors the existence of two-dimensional arrays of very short spikes on the body skin of hornets, not unlike antenna arrays for radar and wireless communication systems. Later, Prof. Ishay and his team also found that the hornet's two antennas produce electricity and include spikes. These three radiation sources enable direction finding – even at great distances – from cooperative targets by wireless communication, allowing a new hypothesis of triangulation and an inverse GPS property for hornets.

In this paper, a hypothetical biological radar for hornets is presented. In particular, we present a hypothesis regarding short spikes that may act as three phased arrays with extremely short monopole antenna elements. Due to their tiny physical dimensions, the frequency range of the antennas was estimated to be beyond 250 GHz, in the THz band. A comparison with other biological radar and direction-finding wireless communication systems is also provided.

1. Introduction

The current progress in wireless positioning systems was set off by recent great improvements in the precision, reliability, and timing of modern Global Positioning Systems (GPS), Digital Signal Processing (DSP), and other technologies. These resulted in a host of innovative military and civilian applications, as well as significant life-saving capabilities. However, on our Earth there exist a number of creatures, mammals, and insects that possess extremely sophisticated and accurate capabilities, the perfection of which Mother Nature has been "working on" for millions of years, and which they use to locate and position their friends and foes. For instance, it is well known that bats have developed superior ultrasonic acoustic radio-detection and ranging (radar) around 20 kHz to detect, locate, and hunt their prey. Elephants, dolphins, whales, and other mammals also have very-low-frequency acoustic wireless systems for radar, communication, and positioning. There are several small insects, such as moths, which possess detection and localization systems for mating and other purposes at very high frequencies, up to the THz range, due to their small physical dimensions. Scientists also study these biological systems today for improving man-made positioning systems, and other purposes.

The late, great entomologist, Prof. Jacob S. Ishay, from the faculty of medicine at Tel-Aviv University, dedicated his life to hornet research. Prof. Ishay installed hornet nests near the window of his laboratory, on the fifth floor of the medicine faculty building of the Tel Aviv university. This was not highly appreciated by his neighbors, although nobody was stung. Several theories have been developed so far in trying to explain how hornets can hunt their prey, easily localize their nests at distances of up to a few kilometer, and how male hornets track and fertilize queens belonging to other nests. Prof. Ishay found that the hornet's body produces a considerable amount of electrical energy by means of photovoltaic and piezoelectric processes [1]. He also identified that hornets cannot operate in darkness, since they use photovoltaic cells as their energy source.

The authors had the privilege of knowing Prof. Ishay as a friend and colleague. He was a true scientist of honor and integrity. Through an electronic microscope, Prof. Ishay and the authors have observed a multitude of very short spikes with three different lengths, located on the center body skin of local oriental hornets. Photos of these

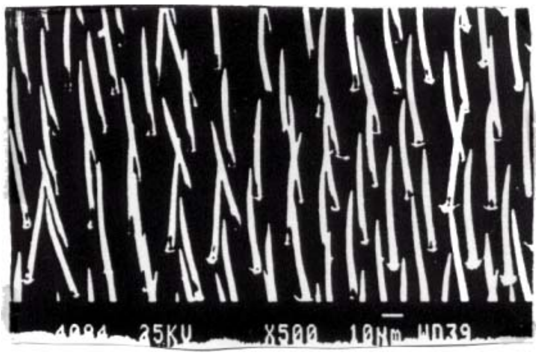

Figure 1a. A photo of the densest hornet phased array ($n = 1$). The spikes were about $L_{s1} = 55$ µm long, spaced 20 µm to 25 µm from each other.

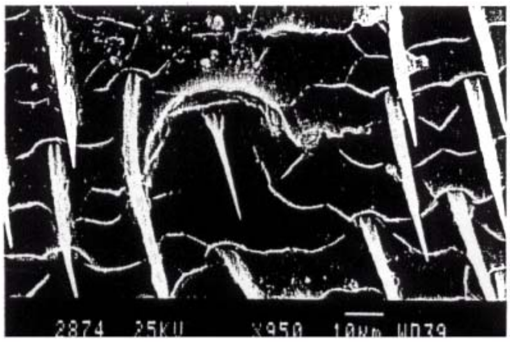

Figure 1b. A photo of the intermediately dense hornet phased array ($n = 2$) (from the same area as Figure 1a). The spikes were about $L_{s2} = 30$ µm long.

spikes are shown in Figure 1 [2]. Prof. Ishay and his team measured the dimensions of the spikes in order to estimate the frequency ranges, considering the estimated length of the spike as a quarter wavelength [3] for optimal radiation. The extremely short length of the hornet's spikes (dielectric antennas) implies extremely high operational frequencies of 100s of GHz, THz, and higher.

Based on our previous experience in radar, radio communications, RFI, direction finding (DF), GPS systems, and the findings of Prof. Ishay, we have arrived at some interesting conclusions [2-4]. The short spikes may act as phased-array dielectric antennas, with extremely short monopole elements transmitting and receiving radio or acoustic signals [5-7]. This is analogous to the well-known acoustic radar tracking and location systems of bats, operating at ultrasonic frequencies from 20 kHz to 200 kHz [8, 9]. However using spike antennas at extremely high frequencies with limited mechanical energy, it is more probable that the signals propagated are carried by EM waves, instead of longitudinal acoustic waves.

The hypothesis developed in this paper assumes that the significant electrical energy in the hornet's body, found and measured by Prof. Ishay [1, 4], is partly converted to EM waves to operate biological radar and direction-finding systems in the THz frequency bands. Calculations show that the hornet's THz radar operating range for detecting and positioning their prey is limited to 10s of meters, which is similar to the operating range of predator bats. Such radar and direction-finding systems are perhaps less developed for honey bees. The bees are more similar to fruit-eating bats that possess less-sophisticated and shorter-distance location systems than those for the insect-eating predator bats [8, 9].

The significantly higher operating ranges required for localizing the hornet's nests can be explained by the operation of the hornet-nest sentinels. The hornet-nest sentinels continuously transmit signals during the daytime that may be received by remote hornets. The remote hornets, even far from their nest, receive the transmitted signals, which help them to localize the exact position of the nest [3, 4]. This can be explained and computed using the Friis line-of-sight (LOS) radio-communication model, rather than the radar equation [10]. The hornet's remote-positioning system can be precisely explained by a triangulation process, similar to an inverse GPS, modeled by a transmitting antenna from the nest sentinels or the queen hornets [3, 11], and three receivers located on the hornet's body and the hornet's two antennas, as will be explained in Sections 3 and 4.

In this paper, we present the hypothetical biological radar of hornets. Our hypothesis suggests that the three different spike lengths represent three transmitting and receiving phased arrays, each operating at a different sub-millimeter wavelength, as implied by the short physical dimensions of the spikes [2, 5]. This hypothesis is supported by the existence of a natural photovoltaic, thermoelectric, and piezoelectric internal generation of energy in the hornet's body, which provides the radio-frequency (RF)

Table 1. The frequency range, wavelengths, spike lengths, atmospheric losses, and dispersion losses at a distance of 10 m from oriental hornet workers [2].

	L_{sn} (µm)	λ_{sn} (µm)	f_{sn} (GHz)	$2A_d$ (dB)	$2A_{at}$ max (dB)
1. Denser phased array	55	220	1365	230	6.0
2. Intermediate phased array	30	120	2500	240	8.0
3. Sparser phased array	140	560	535	215	2.0

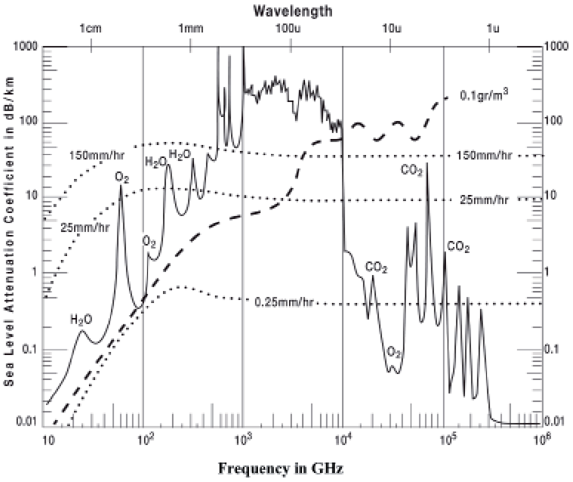

Figure 2. The sea-level atmospheric attenuation coefficient [dB/km] as a function of frequency (lower horizontal axis) for: a gaseous atmosphere (solid line, for 20° C and a water-vapor density of $7.5\ \mathrm{g/m^3}$, clouds, or fog (dashed curve for water droplets $0.1\ \mathrm{g/m^3}$), and various rainfall rates (dotted curves) [10].

energy required for the operation of such a biological radar system [3]. This novel hypothesis could replace those related to the terrestrial magnetic field or pheromone scent trails [4].

2. The Hornet's Biological Radar Tracking: Analysis and Operating Range Computation

Table 1 presents estimated values for the important parameters of the hornet's three phased arrays: the operational wavelength, the frequency ranges, and the propagation-loss limits [3]. The two-way radar free-space line-of-sight dispersion losses, $2A_d$, of the transmitted navigation signal are given in decibels (dB) [6, 10].

In Table 1, L_{sn} is the length of the spikes (belonging to array *n*), and λ_{sn} is the estimated wavelength. From the basic relation

$$f_{sn} = \frac{c}{\lambda_{sn}}, \qquad (1)$$

where $c \approx 3 \times 10^8$ m/s is the velocity of light, and the approximate optimal radiated wavelengths are around $\lambda_{sn} \approx 4L_{sn}$.

The estimated three influential frequency ranges, f_{sn} of the oriental hornet workers are thus around 535 GHz, 1365 GHz, and 2500 GHz: all in the THz frequency band [12]. The dispersion losses, A_d, in the far-field region are given by

$$A_d = 20 \log \frac{4\pi d}{\lambda}\ \text{(dB)}. \qquad (2)$$

For instance, for the sparse phased-array-radar space (wavelength λ_{s3}), the dispersion losses at a line-of-sight distance of $d = 10$ m from the hornet are $A_d = 107$ dB for one-way and $A_d = 215$ dB for two-way operation. Obviously, the high loss levels require highly sensitive receivers and high gain of the (spike) array antennas in order to achieve high detection probability of targets for distances exceeding 10 meters [4, 11].

At millimeter and sub-millimeter wavelengths, the atmosphere contributes additional losses due to molecular frequency resonances and air moisture. The measured mean and maximum atmospheric loss factor α [dB/m] was obtained from the International Telecommunication Union Radio (ITU-R) [10] and Jet Propulsion Lab (JPL) statistical measurement results [11]. The atmospheric losses, $2A_{at}$, at a distance of $d = 10$ m from an oriental hornet at sea level under maximum heavy status cloud humidity conditions, are also presented in Table 1 for the three estimated frequency ranges [3].

For instance, at a distance of 10 m from the hornet under atmospheric conditions, the maximum two-way atmospheric losses for the medium-density phased-array radar would be around 8 dB, and for the sparse phased-array (535 GHz) would be less than 2 dB, as shown in Table 1 and Figure 2. It is thus possible to neglect the atmospheric-propagation loss in most cases, because the inherent line-of-sight propagation dispersion losses exceeding 200 dB dominate [11, 13]. During nighttime, heavy cloud, or rain, hornets are not active, due to the lack of solar and photoelectrical energy, which is mandatory for the operation of their radar system [1, 14].

The estimated sub-millimeter-wavelength range of $120 < \lambda_{sn} \leq 560$ for worker hornets is far lower (by at least one order-of-magnitude) than the classical infrared (IR) wavelength of NdYag (1.06 μm) and CO_2 (10.6 μm) lasers [15, 16]. The hornets' far-IR operating wavelengths are thus not yet common, except in radio astronomy. This may be one of the reasons that our hypothesis has not been validated to date.

The operational distance of the hornets' biological radar localization and tracking system depends on the transmitted power level, frequency, weather, and also on the propagation losses.

The hornet's radar operating range, d_{max}, can be computed using the following classical radar equation [11]:

$$d_{max} = \sqrt[4]{\frac{P_t G_t A_e \sigma}{(4\pi)^2 S_{min}}}, \qquad (3)$$

where the estimated values are [1, 3, 4, 17] as follows. The radiated power is $P_t = 20\ \mu\text{W}$. This is due to the significant photovoltaic power developed by the hornets from the electric energy harvested from the sun, and based on the recent paper of M. Plotkin (the last PhD student of Prof. Ishay) [17]. (The paper shows that the I/V measurements for the oriental hornet gave an I_{sc} of $0.858\ \text{mA/cm}^2$ and a V_{oc} of 0.56 V. For an effective area of $0.5\ \text{cm}^2$ and a fill factor of 50%, the dc power could thus reach more than 120 μW. Assuming a low dc-to-THz conversion efficiency of 20%, an estimated RF power of 20 μW is quite possible. For larger males, queens, German, and destructive Asian hornets, the RF generated power would be enhanced.

The antenna gain is $G_t = 10^3$ (30 dBi), due to the high number of spikes (dielectric antenna elements) in the arrays. The minimum detectable signal is $S_{min} = 10^{-13}$ W. The receiving antenna's effective area is $A_e = 2\times10^{-14}\ \text{m}^2$ The radar cross-sectional (RCS) area for an insect is $\sigma \simeq 10^{-4}\ \text{m}^2$ (for an adult person, it is $\sigma \approx 1\ \text{m}^2$). For frequency bands up to 4 THz at room temperature, the system's thermal noise, P_n, is still dominant over the quantum noise, and limits the minimum detectable signal [6, 14]:

$$P_n = FkTB\,, \tag{4}$$

where $k = 1.38\times10^{-23}$ J/°K is the thermo-dynamical Boltzmann constant at the ambient temperature $T = 300K$ B is the frequency bandwidth (estimated to be less than 1 MHz), and $F \approx 10$ is the noise figure. This gives $P_n \simeq 4\times10^{-14}$ W.

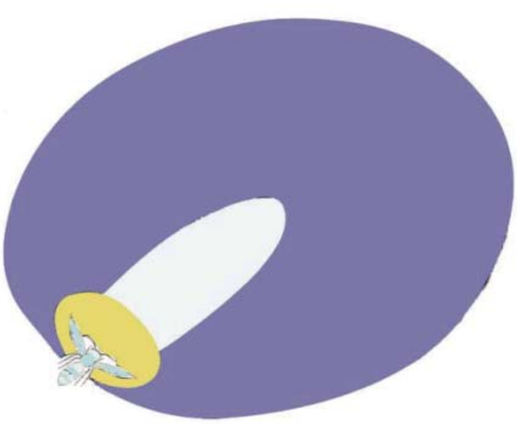

Figure 3. The three-mode tracking mechanism of the hornet's natural radar systems.

Substituting these realistic estimated values into Equation (3), we obtain

$$d_{max} = \sqrt[4]{\frac{2\times10^{-5}\ 10^3\ 2\times10^{-4}\sigma}{(4\pi)^2\ 10^{-13}}} \approx 23\sqrt[4]{\sigma}\ \text{m} \tag{5}$$

The biological radar operational range for a flying hornet to detect and track an adult person is thus about $d = 23$ m, and for a small insect, about 2.3 m. This range is extended because the hornet's cerebral control system may perform a signal-processing pulse-integration process, similar to the case of bats [8, 9]. For an adequate probability of detection and a low false-alarm rate, the operational radar range can be enhanced up to three times to

Table 2. The important antenna parameters of the various spike arrays present on the oriental hornet workers and males [4].

A. Worker's (dielectric antennas) spikes

Types	Length (μm)	Wavelength Range (μm)	Frequency Range (GHz)	Base Diameter (μm)	Tip Diameter (μm)	Relative Number**
Trichoid	22.6	89.4	3340	2.4	Spine-like	100
Placoid	24.7	98.8	3035	4.6*	–	20
Campaniform	11.9	47.6	6300	7	3.3	5
Agmon	8.9	35.6	8430	3.7	Spine-like	2

B. Male's (dielectric antennas) spikes

Types	Length (μm)	Wavelength Range (μm)	Frequency Range (GHz)	Base Diameter (μm)	Tip Diameter (μm)	Relative Number**
Trichoid	20	80	3750	3.5	Spine-like	100
Placoid	27.1	108.4	2770	8.8	3.6	5
Campaniform	11.7	46.8	6400	3.4*	–	20
Agmon	8.2	32.8	9150	3.3	Spine-like	2
Tyloid	253.6	1014.4	295	72.3*	–	1*

*Width, **on a relative scale of 1 to 100

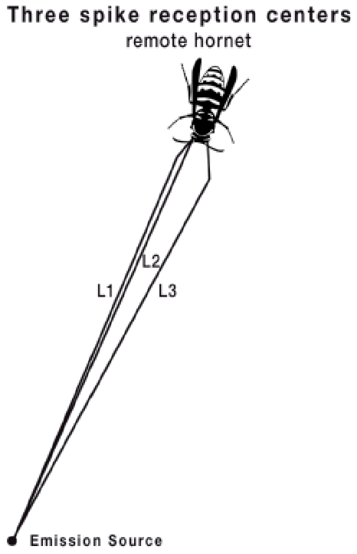

Figure 4. The hornet's communication-based direction-finding technique, with three reception centers, L1, L2, and L3, for remote cooperative target detection, nest localization, or mating queens by the males.

$$7\ \text{m} < d_{max} < 70\ \text{m}\,. \qquad (6)$$

For comparison, it is known that for bats, the operational range of their navigational system extends from a few cm up to 30 m [8, 9]. The extremely-high-frequency (EHF) radio emissions of hornets depend on the weather and light intensity. Under good sunny conditions, significantly higher probabilities of prey detection and tracking accuracy can be obtained [14].

For a radar using a biological switching multimode operation, it is logical that an array with the lowest frequency range, and lower antenna directivity and dispersion losses, is operated first when starting the detection and localization process [13, 16]. Later, when the target is very close and the reflected signal exceeds a higher-threshold power level, the biological radar system would switch to the most-accurate tracking mode, with the highest frequency range and the smallest operation range, as presented in Figure 3.

However, the provided radar analysis and computational results cannot explain the higher detection and localization ranges at which worker hornets can track and reach their nest, or at which male (drone) hornets can join a queen from distances up to a few kilometers.

3. Hornet Communication-Based Direction-Finder Investigation (General Concepts)

It was later shown by a young student of Prof. Ishay, Yafit Agmon, that the two antennas of hornets are also densely covered by numerous short spikes of different lengths [14]. Prof. Ishay therefore named the shorter spikes on the hornet's antennas Agmon (see Table 2). Measurements have shown that the electric voltage, current, and power of the two hornet antennas are significantly high, similar to their body cuticle. In addition, piezo-electrical energy can be generated in the antennas during flight times. The hornet's two antennas and the cuticle thus together provide three different sources of wireless transmission and reception for detection, localization, and tracking of cooperative target echoes, as shown in Figure 4 [4].

The measured spike dimensions are presented in Table 2, including four spike species for hornet workers, as presented in Figure 5, and five species for drones (males), as presented in Figure 6. Table 2 shows the average length, L_{sn}, of the spike species and the estimated frequency ranges obtained for simple monopole spike antennas, where

$$\lambda_{sn} \approx 4L_{sn}\,, \qquad (7)$$

and

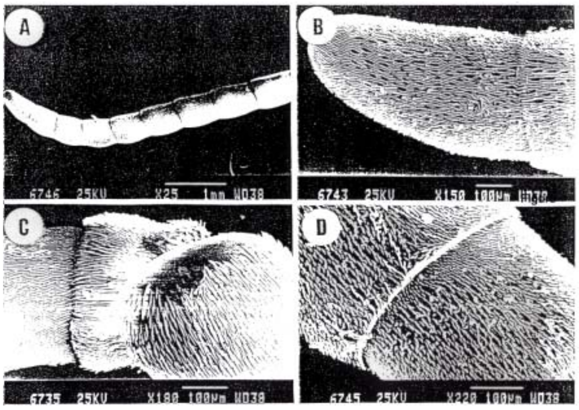

Figure 5. Worker hornet spike arrays: pictures taken in the laboratory of Prof. Ishay using an electronic microscope [4].

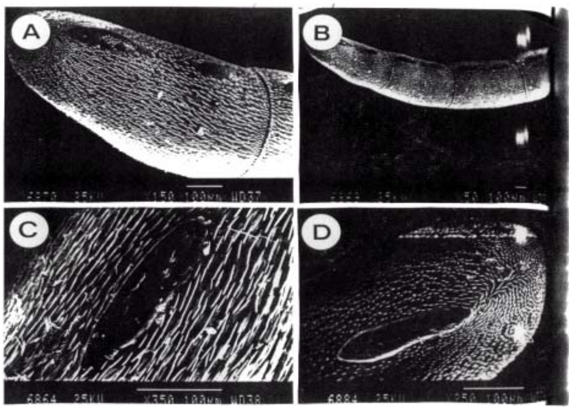

Figure 6. Drone (male) hornet spike arrays: pictures taken with an electronic microscope.

$$f_{sn} \approx \frac{3\times10^5}{4L_{sn}} \text{ GHz.} \tag{8}$$

Table 2 also provides the spike elements' base and tip diameters, and the relative number of spike elements in a scale of one to 100 units.

The photoreceptor elements are not considered here, because of their scarcity and the difficulty in measuring the permittivity and the operational frequency ranges of this stripline configuration. Table 2 shows that the frequency bands of the oriental worker hornets' phased-array antennas may extend from 3035 GHz to 8430 GHz, in the THz band. Most of the spike elements belong to the two lower frequency bands, providing the highest operational range because of the lowest dispersion losses. The scarcer spikes of the two antennas provide the two higher-frequency ranges required for the maximum accuracy for the shorter-distance ranges from the target (the last mile, or more accurately, the last meters). The frequency operating band of the oriental male hornets' antenna phased-arrays may extend from 295 GHz to 9150 GHz. The array operating at 295 GHz, with the lowest density of spikes, provides the longest operational range, due to the lower dispersion losses. However, its directivity is too low, and it can be useful only for initiating the orientation process to detect, track, and mate with the queen hornets.

The highest number of spikes and maximum phased-array directivity are obtained at the highest frequency band of 9150 GHz, where the phased array can provide the highest accuracy for the final tracking steps [14].

It has been previously shown that the radar detection and tracking operational ranges are limited to tens of meters, due to the extremely high losses, which increase at an exponential rate as d^n, where $n \geq 4$. However, the fixed distances between the hornet's two radiating antennas and the cuticle radiation and detection sources suggest a new hypothesis of a radio-communication direction-finding technique [17]. The radio-communication direction-finding technique allows a precise and fast localization and tracking of hornet cooperative targets from the net sentinels or the queen, which may transmit up to THz frequency signals. In these cases, the operational range is therefore extended up to a few kilometers using wireless communication instead of an ordinary radar system. The space dispersion losses increase as d^2 under line-of-sight conditions, compared to the sharper rate of d^4 for radars [14, 18].

This new direction-finding hypothesis, shown in Figure 4, could explain the hornets' ability for tracking over large ranges of up to a few kilometers. This high operational range is computed by simulation, as presented in Section 4.

The hypothesis of an insect's radio-communication system using microwave or IR wavelengths is not new. It was published in a few papers, such as [19, 20], concerning night-flying moths that locate mating partners via a natural far-IR radio-communication link. However, the hypothesis of sub-millimeter radar detecting, tracking, and radio-communication links using direction-finding techniques applied to hornets is new. It should be noted that the military combat aircraft (F18) called the Hornet, and the new Boeing and Northrop Grumman advanced Super Hornet aircraft and radars [21], have no direct relationships to this new hypothesis.

Nowadays, the most popular and useful manmade direction-finding technique is the Global Positioning Satellite (GPS) system. Using the triangulation technique, GPS provides very precise and fast three-dimensional positioning by simultaneously receiving microwave (MW) signals from at least three orbiting transmitting satellite sources [22]. For hornets, the direction-finding technique differs by using millimeter or sub-millimeter signals simultaneously received by three different distant phased-array sources located on the searching hornet's cuticle body, and on its two antennas at fixed distances between themselves. This special biological inverse GPS thus includes one transmitting source from the common operation of several flying hornet sentinels operating in daytime around the nest, and three receiving sources located on a remote hornet, providing indications on the way to reach its nest. We can apply the analogy of a lighthouse beacon illuminating a target in order to attract it. Similar triangulation direction-finding processes can also occur between queen and male hornets.

4. Hornet's Direction Finder: Computation and Simulations

The direction-finding communication-based hypothesis enables us to also explain how males from remote nests can track and localize queen hornets for mating purposes. The direction-finding operational range can be computed using the Friis line-of-sight free-space equation, considering that for the extremely short waves transmitted by the hornets, more than 60% of the first Fresnel ellipsoid of the link is generally free of obstacles [6]:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2, \tag{9}$$

or

$$\frac{P_r}{P_t} = \frac{G_t G_r c^2}{16\pi^2 f^2 d^2}, \tag{10}$$

where P_r and P_t (watt) are the power at the receiver antennas' inputs (male) and the power radiated by the transmitter antennas (queen), respectively. G_t and G_r are the transmitter and the receiver antennas' array gains, respectively. f is the operational frequency in GHz, and d is the estimated operational distance (in meters).

From Equation (10) we obtain

$$d = \sqrt{\frac{P_t G_t G_r 9\times10^{-2}}{160 P_r f^2}} . \qquad (11)$$

The maximum operational range is obtained from the nondirective minimum frequency band of 295 GHz, shown in Table 2 for initial detection of the queen's position by the males. The following typical realistic values were used in the simulations: $P_t = 2\times10^{-5}$ W, $P_r = 4\times10^{-14}$ W, as shown previously for clear atmospheric conditions; G_t and G_r were each around 1000 (30 dBi); and we found $d \approx 1150$ m.

The direction-finding hypothesis can also explain the localization and the return to their nest of distant hornet workers. Using the former natural radar detection and tracking techniques, the maximum hornet operational range is limited to only a few tens of meters, as previously shown using Equation (5). However, it is also well known that hornets can directly find their way to their nest up to a distance of several kilometers. To enable detecting and tracking the location of the nest from these far distances, several sentinel worker hornets simultaneously ventilate their wings as a group near the nest [4] to generate radio energy during the daytime, and radiate their sub-millimeter signals in a similar fashion, as in the case of a lighthouse beacon.

The emission from multiple identical radiation sources can be received by the three phased arrays of a remote hornet. These phased arrays are located at fixed mutual distances on the hornet, and enable the direction-finding system to localize and track the nest by a triangulation process [11, 17].

The maximum distance of direction-finding communication, d, of remote hornets from their nest can also be computed using Equation (11). It was shown that the most efficient radiation was at the worker hornet's lowest frequency range of 535 GHz (Table 1). Assuming $P_t = 2\times10^{-5}$ W, $P_r = 4\times10^{-14}$ W, and $G_t = G_r = 1000$ (30 dBi), we obtained $d_{max} \approx 650$ m. For the oriental hornets, d_{max} is slightly reduced, due to the additional atmospheric losses for a distance of 1 km at 535 GHz[3, 10, 17]. However, the diversity technique achieved using the common sub-millimeter radiation from several transmitting hornets and integration of pulse transmissions can still enhance the operational range by about a factor of three or even more [14]. Using the same equations for the bigger German hornets, operating at lower frequencies, results in a significantly higher d_{max} under line-of-sight propagation conditions.

5. Preliminary Experiment, Test Results, and Discussion

The validation of the proposed novel hypothesis of natural radar tracking and communication-based direction-finding systems affecting the flight of hornets was very complex in the past. This was due to the rarity and high price of measurement equipment, radio sources and detectors, operating at frequency ranges exceeding 100 GHz (sub-millimeter waves). As shown in Tables 1 and 2, the estimated radiation and detection frequencies for oriental hornet workers were from 535 GHz to 8430 GHz, and for males (drones) they were from 295 GHz to 9150 GHz [4, 14].

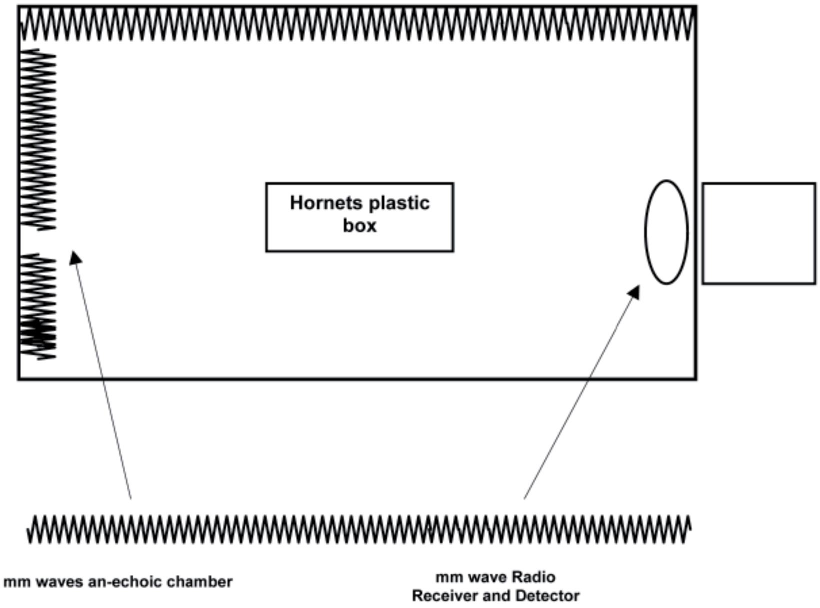

Figure 7. A schematic diagram of the hornet radiation experiment [3, 4].

Prof. Ishay also investigated the German hornets (wasps) Paravespula Germanica. For the (German) European wasps, the maximum length of the spikes is close to 0.5 mm, which corresponds to a minimum estimated frequency range of around 150 GHz. The existence of these longer spikes can be attributed to the high rainfall, cloud, and foliage conditions in central Europe. These long spike lengths enable satisfactorily higher radar distance tracking and communication direction-finding systems at millimeter rather than sub-millimeter wavelengths.

In 2002, Prof. Ishay and the authors tried to test the first hypothesis regarding hornets in a best qualified laboratory state-of-the-art start-up R&D company at the Technion research center campus in Haifa (Israel). The laboratory facilities included a millimeter-wave anechoic chamber, and two bulky, sensitive, and accurate measurement receivers, operating at fixed frequencies of 140 GHz and 220 GHz. Prof. Ishay built an experimental setup with two glass-covered boxes. The first one included about 50 German hornets, and the second had tens of the Oriental type of workers, and six male hornets. A schematic diagram of the hornet radiation experiment is shown in Figure 7 [3, 4].

Following a long calibration process separately for each hornet box, when held in a dark anechoic chamber, the boxes were illuminated by a strong projector light for a period of a few minutes, in order to enable the hornets to better radiate. When the hornets are flying, it may be that they develop additional electric energy from the piezo-electric effect, which is partially converted to more RF emission in the THz frequency range.

In all the experiments with the German hornet box, the 140 GHz receiver systematically showed an increase of about 1% in the ratio of the received to the background radiation intensities under illumination, when compared to the dark conditions. However, in several cases with the 220 GHz receiver, the intensity ratio decreased under illuminated conditions. These results were correlated to the estimated German wasp minimum radiation frequency of 150 GHz, which was far from the 220 GHz range. By comparison, the ratio intensity measurement results with the Oriental hornets showed contradictory results for both the 140 GHz and 220 GHz receiver cases. This may have been due to the significant frequency difference within the expected oriental hornet radiation frequency bands.

Our main conclusions from the preliminary experimental results were:

1. The partially affirmative results obtained with the German wasps at 140 GHz were encouraging, but not sufficient for a conclusive proof of our hypothesis.

2. The hornets must be flying in order to supply additional piezo-electric energy, besides the mandatory illumination conditions for optimal radiation. This can be achieved by producing waves of appropriate frequency (using a horn, for instance) in order to stimulate the tested hornets to fly, and/or by allowing some of them to be free outside of the box in the anechoic chamber.

3. At least a frequency sweeper with a range of 140 GHz to 220 GHz is required, to detect the reception of the peak radiation of the German hornets at the precise main frequency. This may be sufficient to prove the hypothesis of millimeter-wave radar tracking for the German wasps, but not enough for the investigated Oriental hornets operating at significantly higher frequency ranges, where very rare and expensive sub-millimeter-wave sources, chambers, and detectors existed at this time.

4. Prof. Ishay suggested testing hornets held away from their nests by affecting their spike location system, which may prevent them from finding their nest. Unfortunately, he could not complete these experiments and his laboratory was closed following his death.

6. Collaboration Required to Prove and Benefit from Our Hornet Hypothesis

The future measurements and experiments to completely confirm our hornet hypothesis and usefully utilize the results would require a tight collaboration between:

1. Expert entomologists in hornets (or in the worst case, in bees, which may be less performing than hornets), with a leading, well-equipped laboratory, similar to the laboratory of the late Prof. Ishay.

2. Wireless communication or/and radar experts also working in the THz frequency ranges using up-to-date equipment in the field [23-25].

There are two kinds of tests required to prove our hypothesis: positive and negative tests.

The positive tests would be similar to those we have done as described in Section 5. However, they would require the use of sophisticated, sensitive, and accurate variable-frequency receivers or spectrum analyzers in the THz ranges to detect the hornets' emissions, especially when they are flying. This required novel equipment was not yet available when we performed our experiments. It is now available in several laboratories. It may also be possible to expose the hornets to modern THz variable-frequency transmitters or signal generators and to test their reactions.

The negative experiments, of damaging the spikes of the hornets and observing if they are affected and hence unable to find their required direction, were suggested by the late Prof. Ishay. However, they were not done because he became ill. It is also suggested to use different electrical shielding materials between some hornets and their nest, and to test if they loose their direction in the case of strong shielding. These negative experiments are easier to do, but are less important and conclusive than the positive experiments described.

7. Final Conclusions

Experiments have been conducted to investigate the functions of the spikes on the body skin and antennas of hornets. These were observed by the late, great entomologist, Prof. Jacob S. Ishay, using an electronic microscope. These have led to the new hypothesis of a natural complex radar navigation system, referring also to Prof. Ishay's discovery of a large amount of electric energy produced in the bodies and antennas of the hornets, partly from biological photovoltaic cells [1-3, 17, 26].

Our computational results show that the radar tracking and detection operational ranges are limited to tens of meter, even for large radar cross sectional areas. The hypothesis of the hornet males tracking the queens and workers, localizing their nests at distances of up to a few kilometers, were developed, using the concept of direction-finding and inverse-GPS technique based on radio communication, instead of a radar-based system. The possibility of sub-millimeter wave radiation transmission towards three transmitting and receiving wireless communication radiation and detection centers, included on a single remote hornet, were also suggested. This may enable direction-finding radio-communication localization and tracking of cooperative hornet targets up to an operational range of a few kilometers [4, 14].

Our fascinating hypothetical hornet radar and direction-finding wireless communication systems may explain their short-range hunting radar and astonishing three-dimensional long-range guidance and localization abilities. However, these have yet to be confirmed by precise measurement results that correlate with the parameters of the sub-millimeter-wave radiated power sources. The estimated natural hornet's radar-system wavelength bands are far beyond the usable longer radio microwave and millimeter-wave bands, and shorter than the infrared bands. The likelihood of detecting the hornet's radiation in the THz frequency band to date has therefore been very small, as the development of equipment was in its infancy [12]. However nowadays, with the huge progress, developments, new applications, and the availability of accurate and sensitive measurement equipment in the THz bands, it easier and more probable to prove our hypothesis [23-25]. Cooperation with entomological experts in hornets and bees is required to validate our hypothesis and to replace the actual hypotheses on hornet performance of long-distance detection and direction finding due to the terrestrial magnetic fields or pheromone scent trails [17, 26]. Validation of our proposed hypothesis may open new horizons for the existence of other similar three-dimensional insect or bird radar and direction-finding systems. Furthermore, it could also be useful for research on flying insects and birds, and on novel improved sub-millimeter-wave improved wireless systems for new applications.

It has also been published in scientific and popular reviews that honey bees can be used for detecting explosives and drugs [28]. However, the predator hornets are more skilled for these applications than bees, whose main functions are to provide honey and to pollinate the flora. It is also very interesting to investigate the possibilities of applying nanotechnology circuitry on cyborg hornets for influencing them to fulfill similar tasks, such as what has been implemented by DARPA and other R&D institutions with bats and insects for intelligence and other remote-sensing missions [29].

Recently, huge hornets from the far east invaded France, Italy, and neighboring countries in Europe. They are exterminating honey bees, the contribution to nature and agriculture of which is tremendous [30]. Expert use of hornets' advanced tracking and localization systems may also help in protecting the bees, which may also be affected from polluted radiation by the numerous new wireless systems operating at increased frequency ranges, such as cellular phones. The recent threats to honey bees from the big Asian yellow-legged hornets could be reduced or solved using cyborg hornets and the results of the natural radar and wireless-communication materials developed in this paper and in the references [29-31].

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