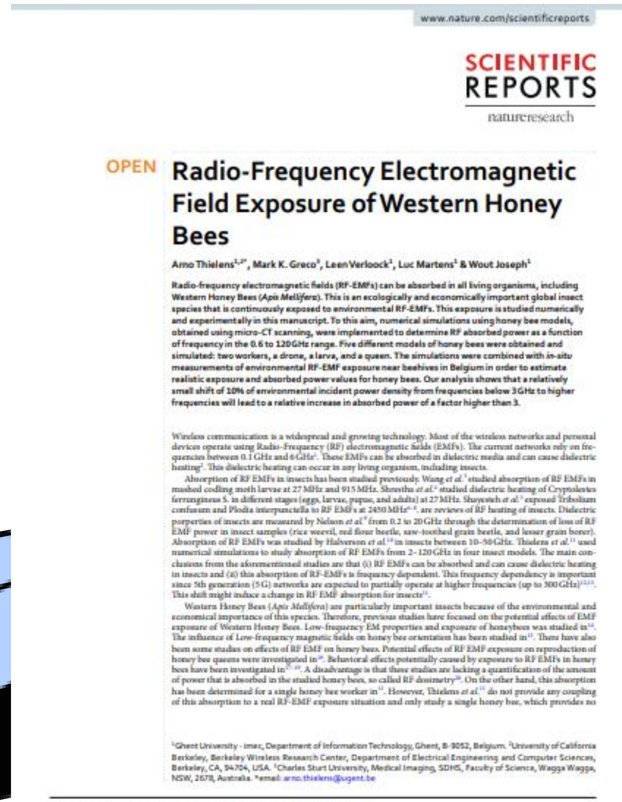
Literature Review:

Radio-Frequency Electromagnetic Field Exposure of Western Honey Bees

by Arno Thielens, Mark K. Greco, Leen Verloock, Luc Martens, Wout Joseph



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Radio-Frequency Electromagnetic Field Exposure of Western Honey Bees

Arno Thielens[1,2*], Mark K. Greco[3], Leen Verloock[1], Luc Martens[1] & Wout Joseph[1]

Radio-frequency electromagnetic fields (RF-EMFs) can be absorbed in all living organisms, including Western Honey Bees (*Apis Mellifera*). This is an ecologically and economically important global insect species that is continuously exposed to environmental RF-EMFs. This exposure is studied numerically and experimentally in this manuscript. To this aim, numerical simulations using honey bee models, obtained using micro-CT scanning, were implemented to determine RF absorbed power as a function of frequency in the 0.6 to 120 GHz range. Five different models of honey bees were obtained and simulated: two workers, a drone, a larva, and a queen. The simulations were combined with *in-situ* measurements of environmental RF-EMF exposure near beehives in Belgium in order to estimate realistic exposure and absorbed power values for honey bees. Our analysis shows that a relatively small shift of 10% of environmental incident power density from frequencies below 3 GHz to higher frequencies will lead to a relative increase in absorbed power of a factor higher than 3.

Wireless communication is a widespread and growing technology. Most of the wireless networks and personal devices operate using Radio-Frequency (RF) electromagnetic fields (EMFs). The current networks rely on frequencies between 0.1 GHz and 6 GHz[1]. These EMFs can be absorbed in dielectric media and can cause dielectric heating[2]. This dielectric heating can occur in any living organism, including insects.

Absorption of RF EMFs in insects has been studied previously. Wang *et al.*[3] studied absorption of RF EMFs in mashed codling moth larvae at 27 MHz and 915 MHz. Shrestha *et al.*[4] studied dielectric heating of Cryptolestes ferrugineus S. in different stages (eggs, larvae, pupae, and adults) at 27 MHz. Shayesteh *et al.*[5] exposed Tribolium confusum and Plodia interpunctella to RF EMFs at 2450 MHz[6–8]. are reviews of RF heating of insects. Dielectric porperties of insects are measured by Nelson *et al.*[9] from 0.2 to 20 GHz through the determination of loss of RF EMF power in insect samples (rice weevil, red flour beetle, saw-toothed grain beetle, and lesser grain borer). Absorption of RF EMFs was studied by Halverson *et al.*[10] in insects between 10–50 GHz. Thielens *et al.*[11] used numerical simulations to study absorption of RF EMFs from 2–120 GHz in four insect models. The main conclusions from the aforementioned studies are that (i) RF EMFs can be absorbed and can cause dielectric heating in insects and (ii) this absorption of RF-EMFs is frequency dependent. This frequency dependency is important since 5th generation (5G) networks are expected to partially operate at higher frequencies (up to 300 GHz)[12,13]. This shift might induce a change in RF EMF absorption for insects[11].

Western Honey Bees (*Apis Mellifera*) are particularly important insects because of the environmental and economical importance of this species. Therefore, previous studies have focused on the potential effects of EMF exposure of Western Honey Bees. Low-frequency EM properties and exposure of honeybees was studied in[14]. The influence of Low-frequency magnetic fields on honey bee orientation has been studied in[15]. There have also been some studies on effects of RF EMF on honey bees. Potential effects of RF EMF exposure on reproduction of honey bee queens were investigated in[16]. Behavioral effects potentially caused by exposure to RF EMFs in honey bees have been investigated in[17–19]. A disadvantage is that these studies are lacking a quantification of the amount of power that is absorbed in the studied honey bees, so called RF dosimetry[20]. On the other hand, this absorption has been determined for a single honey bee worker in[11]. However, Thielens *et al.*[11] do not provide any coupling of this absorption to a real RF-EMF exposure situation and only study a single honey bee, which provides no

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The Big Picture...

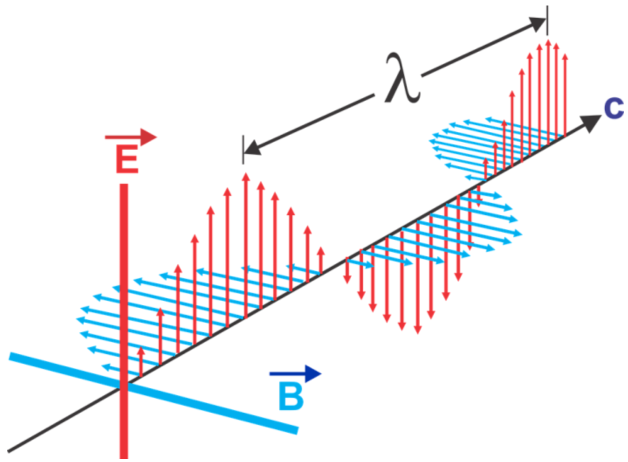
$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$

$$\vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t}$$

$\Rightarrow$



~ 0.1 GHz ... 6 GHz

5G networks: ~ 300 GHz

$\Rightarrow$

Reproduction of queen bees

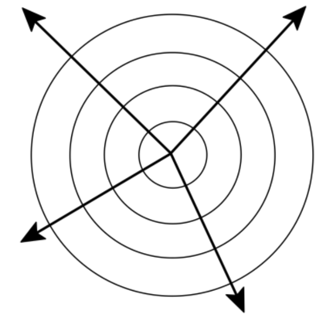
Behavioral effects

Developmental effects

The Mechanism...

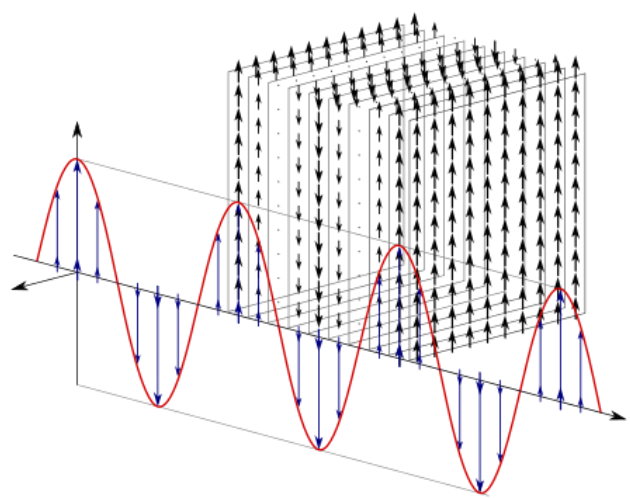
$$\mu_0\epsilon_0\frac{\partial^2\vec{E}}{\partial t^2} - \vec{\nabla}^2\vec{E} = 0$$

$$\mu_0\epsilon_0\frac{\partial^2\vec{B}}{\partial t^2} - \vec{\nabla}^2\vec{B} = 0$$



$$\Downarrow$$

Fraunhofer far-field limit: bees $> 2D^2/\lambda$ away from the electromagnetic source



The Mechanism...

$$
\begin{aligned}
\text{The Poynting vector is } \vec{S} &= \frac{1}{\mu_0}\vec{E}\times\vec{B} \\
\text{for plane, monochromatic light...} &= \frac{1}{\mu_0}E_0\cos(kz-\omega t+\delta)\hat{x}\times B_0\cos(kz-\omega t+\delta)\hat{y} \\
&= \frac{1}{\mu_0}\frac{1}{c}E_0^2\cos^2(kz-\omega t+\delta)\hat{z} \\
&= \sqrt{\frac{\epsilon_0}{\mu_0}}E_0^2\cos^2(kz-\omega t+\delta)\hat{z} \\
&= \epsilon_0\sqrt{\frac{1}{\epsilon_0\mu_0}}E_0^2\cos^2(kz-\omega t+\delta)\hat{z} \\
&= \epsilon_0 c E_0^2\cos^2(kz-\omega t+\delta)\hat{z} \\
\langle S\rangle &= \frac{1}{2}c\epsilon_0 E_0^2 \equiv \text{Intensity} \\
\text{Generally, then, Intensity} &\propto E_0^2
\end{aligned}
$$

The Mechanism…

$$\langle S \rangle = \frac{1}{2} c \epsilon_0 E_0^2 \equiv \text{Intensity}$$

$\epsilon_0 \equiv$ permittivity of free space

…But we are working with materials…

$\epsilon \equiv$ permittivity of the material

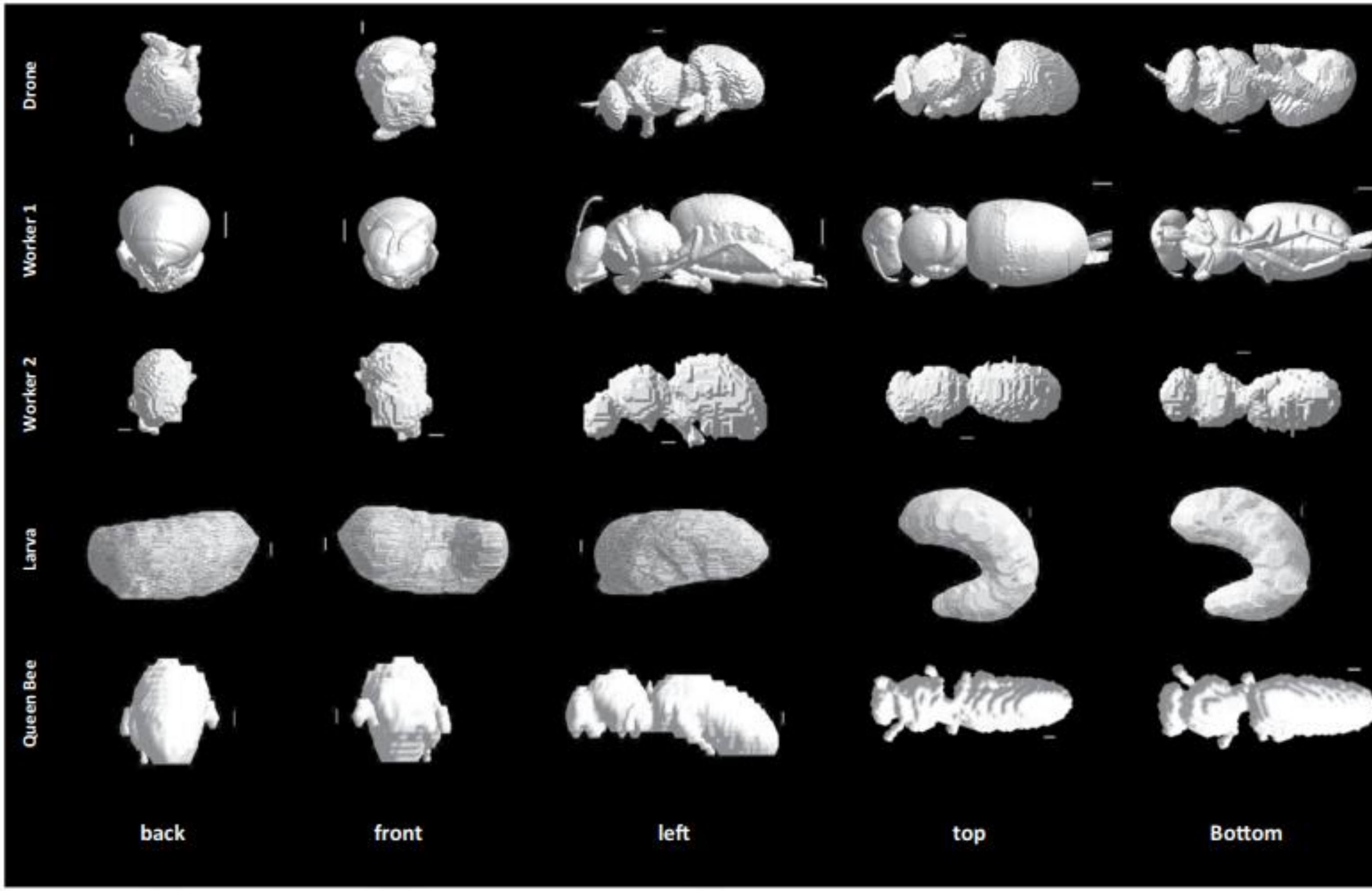
$\frac{\epsilon}{\epsilon_0} \equiv \epsilon_r$ (usually > 1), the so-called dielectric constant.

	0.6 GHz	1.2 GHz	2 GHz	3 GHz	6 GHz	12 GHz	24 GHz	60 GHz	120 GHz
Maximal grid step (mm)									
Larva	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1
Others	0.1	0.1	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Simulated Periods									
Worker Bee 1	20	30	60	30	30	30	30	40	40
Others	10	20	20	30	30	30	30	30	30
ε_r	45.6	44.2	39.9	38.8	38.0	28.6	14.9	7.018	5.46
σ (S/m)	0.688	0.924	1.35	2.05	5.05	12.0	21.1	27.9	29.2

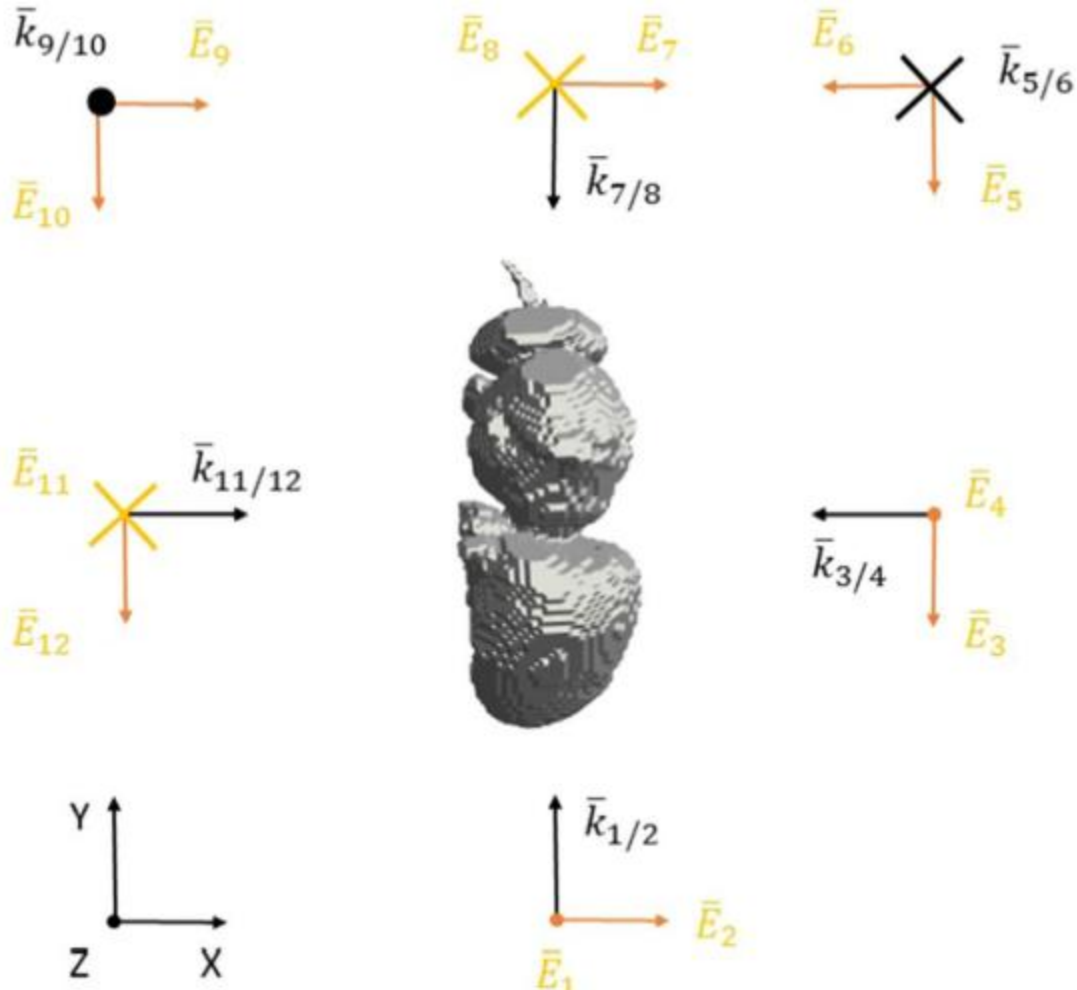
Good conductors (large σ) have $\epsilon_r \sim 1$
Poor conductors (small σ) have $\epsilon_r \gg 1$

Table 1. Simulations Settings and Dielectric Properties of the Honey Bees.

MicroCT Scan

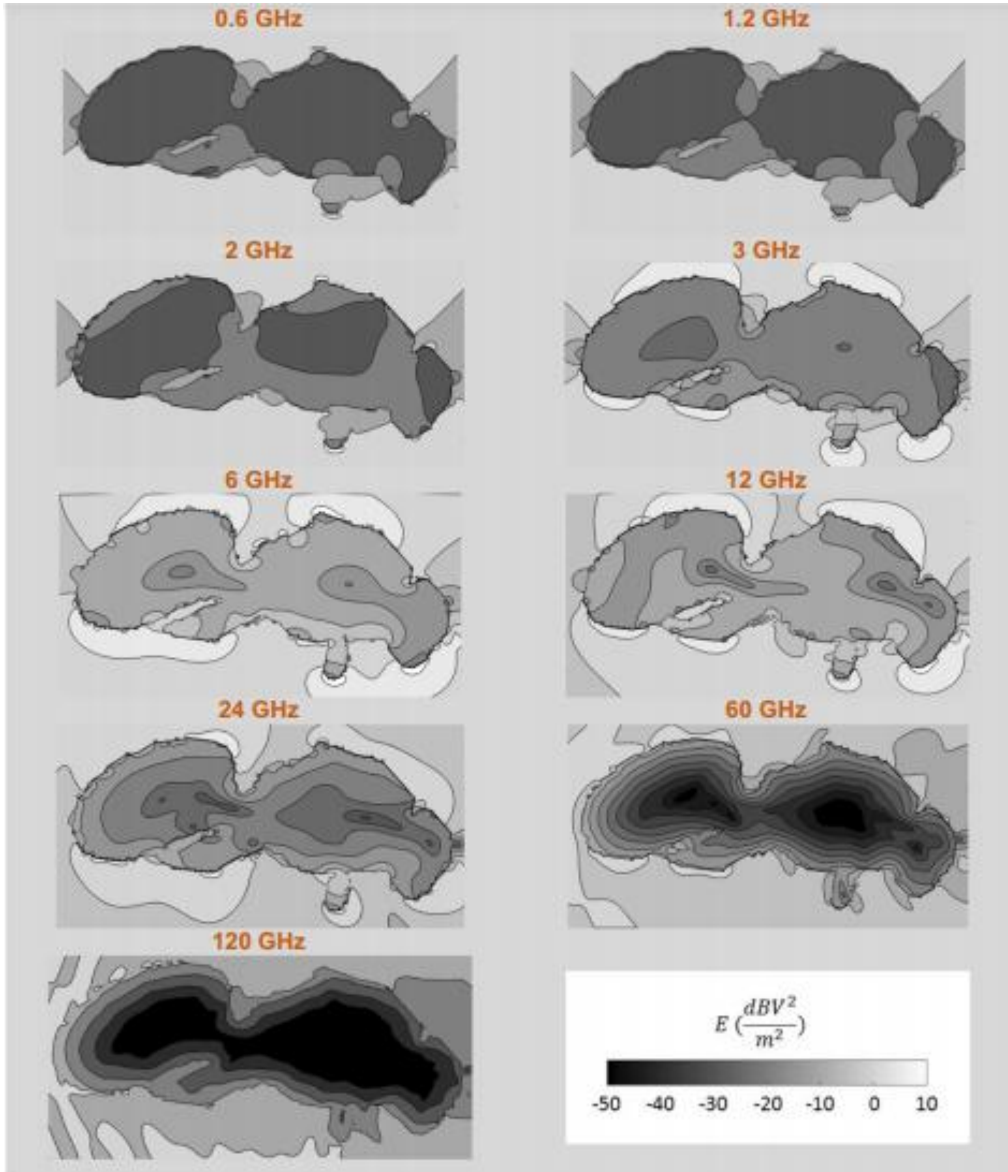


Finite-Difference Time-Domain (FDTD) method



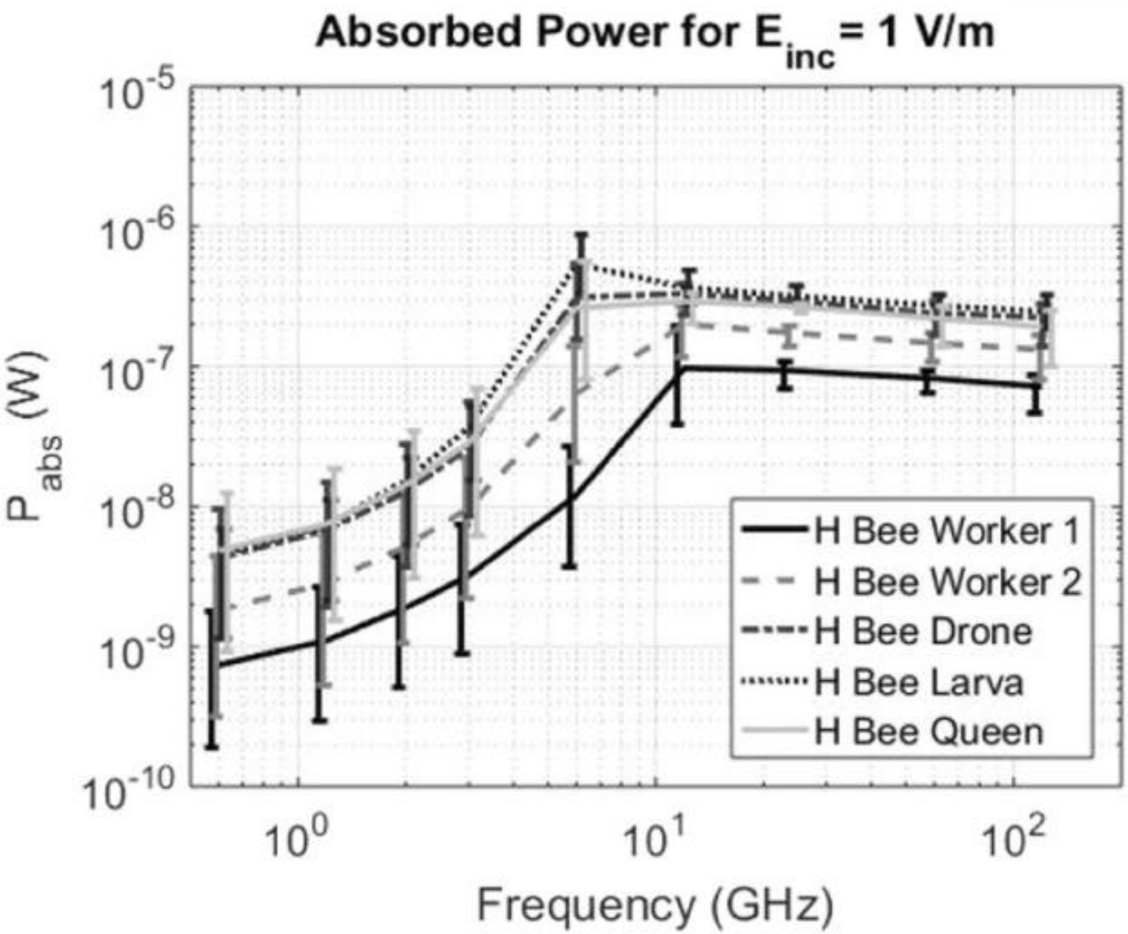
12 (plane waves) $\times$ 9 (frequencies) $\times$ 5 (honey bees) $=$ 540 simulation results.

Numerical solution...

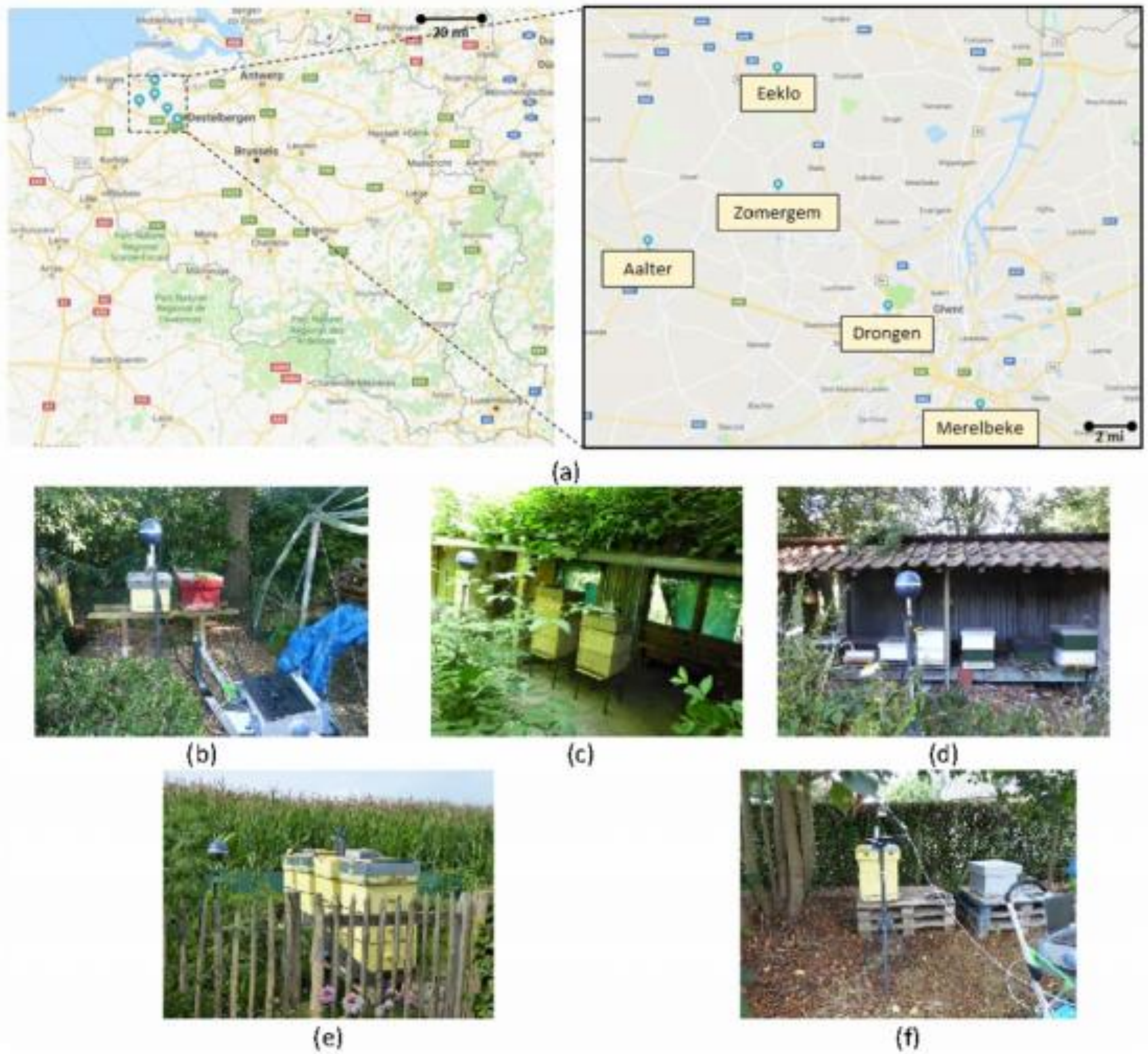


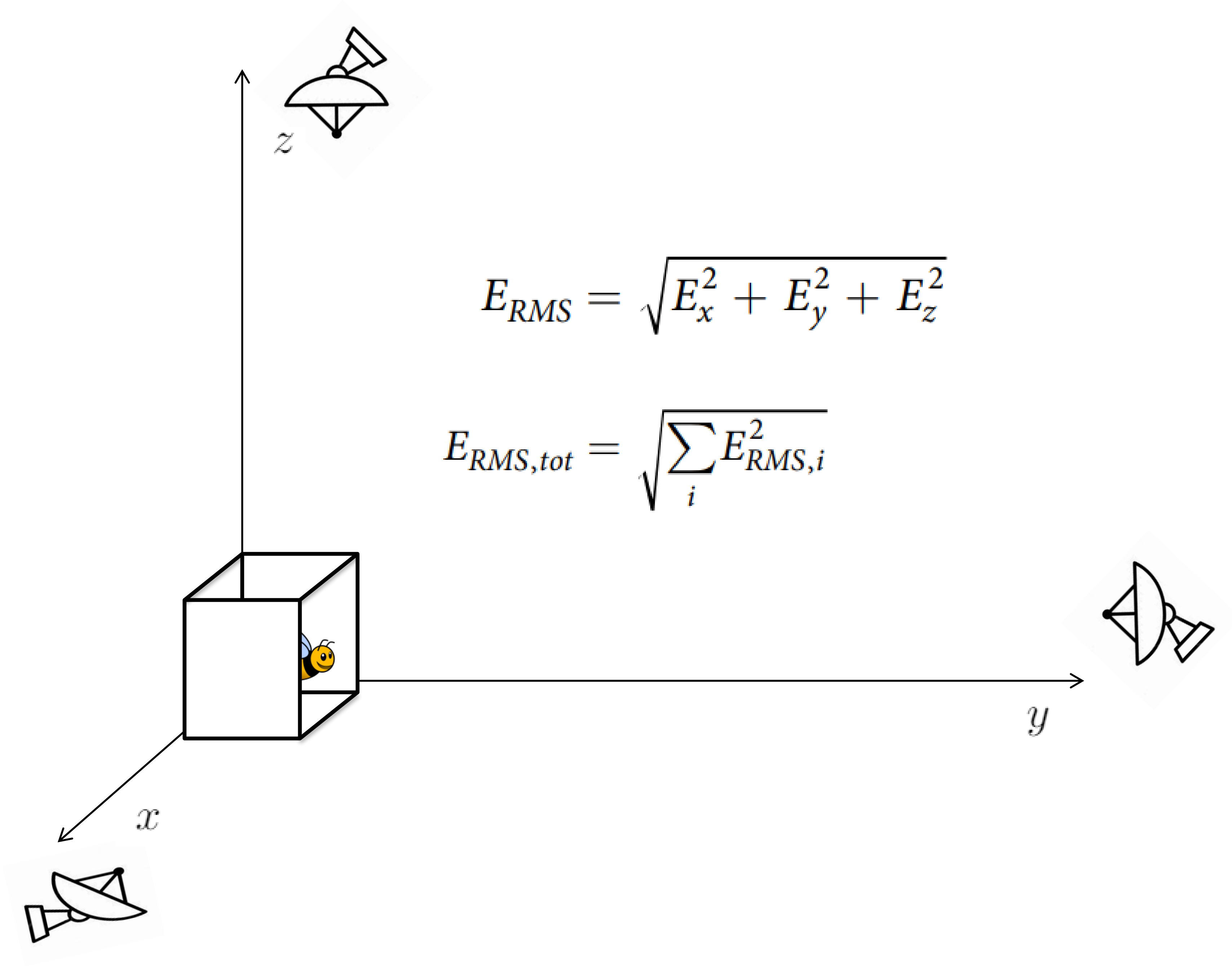
Calculating the power...

$$P_{abs} = \int_V \sigma \times |\overline{E}_{int}|^2 . \, dV$$



Measuring $\vec{E}_{\text{inc}}$...





$$E_{RMS} = \sqrt{E_x^2 + E_y^2 + E_z^2}$$

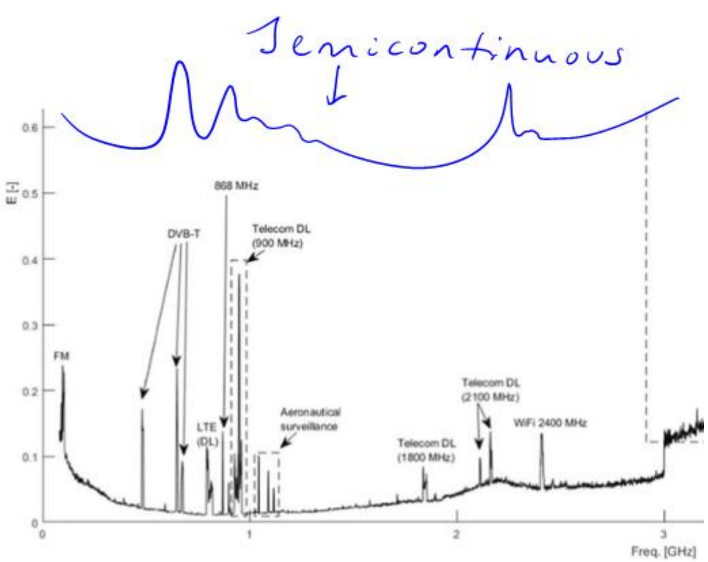
$$E_{RMS,tot} = \sqrt{\sum_i E_{RMS,i}^2}$$

Measured E_{inc} strength...

The names of the different locations

Location	Maximum E-field (1 s interval) (V/m)	Avg E-field (1 s interval) (V/m)
Aalter	0.430	0.272
Merelbeke	0.233	0.1675
Eeklo	0.652	0.532
Zomergem	0.665	0.346
Drongen	0.397	0.297
Average	0.503	0.344

Take the average of these quantities, giving the parameter $E_{RMS,avg}$



Estimate of actual absorbed power in honeybees

$$P_{abs,real}(p) = p \times \frac{E^2_{RMS,avg}}{1\ V^2/m^2} \times P_{abs,av}(f > 3\ GHz) + (1-p) \times \frac{E^2_{RMS,avg}}{1\ V^2/m^2} \times P_{abs,av}(f < 3\ GHz)$$

$$P_{abs,av}(f > 3\ GHz) = \frac{1}{5}\sum_{i=1}^{5} P_{abs}(f_j) \qquad f_j = 6, 12, 24, 60, 120\ GHz.$$

$$P_{abs,av}(f < 3\ GHz) = \frac{1}{4}\sum_{i=1}^{4} P_{abs}(f_i) \qquad f_i = 0.6, 1.2, 2, 3\ GHz.$$

Estimate of actual absorbed power in honeybees

Fraction < 3 *GHz* $(1-p)$ (%)	Fraction > 3 *GHz* p(%)	$P_{abs,real}(p)(nW)$				
		Drone	**Worker 1**	**Worker 2**	**Larva**	**Queen Bee**
100	0	0.63	0.010	0.26	0.73	0.71
90	10	2.5	0.57	1.2	3.0	2.3
80	20	4.3	1.0	2.1	5.3	3.9
70	30	6.2	1.5	3.1	7.6	5.6
60	40	8.0	2.0	4.0	9.9	7.2
50	50	9.8	2.4	5.0	12	8.8
40	60	12	2.9	5.9	15	10
30	70	14	3.4	6.9	17	12
20	80	15	3.9	7.8	19	14
10	90	17	4.3	8.8	22	15
0	100	19	4.8	9.7	24	17

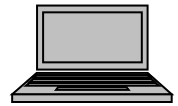
low freq.

high freq

Table 4. Absorbed power in the four studied insects for an incident electric field strength of 0.06 V/m, distributed uniformly over frequencies lower and higher than 3 GHz for different relative fractions.

Conclusion

The simulations use the finite-difference time-domain technique to determine the electromagnetic fields in and around five honey bee models exposed to plane waves at frequencies from 0.6 GHz up to 120 GHz. These sim-



E_{int}

decrease in P_{abs} is observed for all studied honey bees between 12 and 120 GHz. RF exposure measurements were executed on ten sites near five different locations with bee hives in Belgium. These measurements resulted in an average total incident RF field strength of 0.06 V/m, which was in excellent agreement with literature. This value

$$\langle S\rangle = \frac{1}{2}c\epsilon_0 E_0^2 \equiv \text{Intensity}$$

$$P_{abs} = \int_V \sigma \times |\overline{E}_{int}|^2 . \, dV$$

was used to assess P_{abs} for those honey bees at those measurement sites. A realistic P_{abs} is estimated to be between 0.1 and 0.7 nW for the studied honey bee models. Assuming that 10% of the incident power density would shift

Conclusion

0.1 and 0.7 nW for the studied honey bee models. Assuming that 10% of the incident power density would shift to frequencies higher than 3 GHz would lead to an increase of this absorption between 390–570%. Such a shift in frequencies is expected in future networks.

↓

Non-linear response: we should be extra-careful with the types of EM waves we use to carry information.

Additional considerations

insects in free space. In reality, honey bees might cluster, creating a larger absorption cross section and potentially higher absorption at lower frequencies.

It is expected that the micro-CT models used in this study lead to a better estimation of P_{abs} and the spatial distribution of the electric fields than approximate models such as ellipsoids or cylinders[37].

Future research. Our future research will focus on executing exposure measurements of insects in order to validate the RF-EMF P_{abs} values and the dielectric parameters. Additionally, we would like to execute thermal simulations of honey bees and other insects under RF-EMF exposure. Finally, we aim to work on the development of more insect phantoms, with more spatial accuracy and potentially several independently identified tissues.

References

David Griffiths. *Introduction to Electrodynamics*, 2nd ed. Pearson. 200-204. 2015.

Radio-Frequency Electromagnetic Field Exposure of Western Honey Bees. Arno Thielens et al. *Nature.* 16 January 2020. https://www.nature.com/articles/s41598-019-56948-0.

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