

Digital twins as epistemic engines for sensing electromagnetic interactions in western honey bees

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Abstract— Digital twins are an important means of gaining insight into aspects of reality that are otherwise difficult to access. They prove particularly successful in bioelectromagnetics e.g. in the context of electromagnetic (EM) dosimetry where inner parts of exposed biological organisms are not amenable to direct measurement. We employ a (micro-) dosimetric approach that uses digital twins of bees to assess whether resonant energy uptake from EM waves at 5G or 6G mobile communication frequencies complies with ICNIRP exposure limits for the general public. It doesn't. Digital twins can be expanded into virtual ecosystems to analyze bee-plant interactions or to implement radar-based "beehive checkpoints" that track bee traffic and payloads while deterring hornets, rendering digital twins epistemic engines.

Keywords—bioelectromagnetics, electromagnetic exposure, micro-dosimetry, digital twins, insect monitoring, THz radar, 3D printing

I. INTRODUCTION

Western honeybees (WHBs) are vital for global pollination and ecosystem stability, making their health and monitoring essential for biodiversity and food security. WHB populations have declined sharply since the early 2000s, mainly due to widespread pesticide use, habitat loss and other anthropogenic stressors [1] that may potentially include electromagnetic (EM) exposure. As digital twins we use *multiscale* computational EM models to capture the size differences between microstructures (e.g., organelles, cells) and larger biological systems (e.g., tissues, organs, whole organisms). To analyze EM absorption and resulting temperature rises, we employ *multiphysics* (electro-thermal) models that couple EM field equations with models for thermal conduction. Understanding how high-frequency radiation affects WHBs is crucial. Yet, the effects of mm-wave and THz radiation on insects, especially WHBs, remain largely unexplored, underscoring the need for comprehensive studies that address both potential risks and applications, including non-invasive, real-time as well as selective insect monitoring.

II. EXPOSURE LIMITS IN HONEY BEES

A comprehensive review by the Swiss Federal Office for the Environment [2] noted a lack of systematic studies on EM exposure risks, especially regarding a potential resonant energy uptake at wavelengths comparable to insect sizes. In this context, a new digital twin – a honeybee – is introduced. Initial FDTD simulations (EMPIRE XPU) on a simple *homogeneous* WHB model under frontal plane-wave illumination [3] are shown in Fig. 1 and reveal strong electric field penetration up to 40 GHz. Above 100 GHz, the WHB's interior is largely field-free, while scattering from wings, legs, and antennae becomes more pronounced.

These findings are insightful but require further study using an improved, *heterogeneous* WHB digital twin. EM material parameters of wings, cuticle, organs, and the full bee were measured in the Ka- (26.5–40 GHz) and D-bands (110–170 GHz) and extrapolated as corresponding dielectric functions

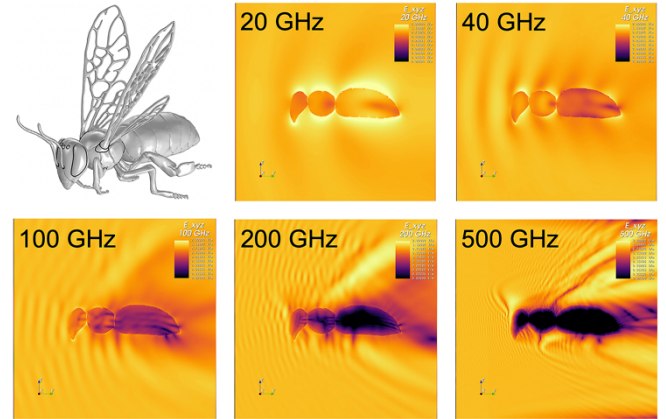


Fig. 1. Digital twin of a honeybee (top left, homogeneous version). EM exposure scenario is simulated using the 3D FDTD simulation platform (EMPIRE XPU) having a plane EM wave incident from the front. The field distribution of the time-averaged electric field strength is shown in the vertical longitudinal section through the bee (sagittal plane) at the indicated frequencies (color code: light yellow: 2 V/m; black: 0.02 V/m).

to the extended frequency range of 1–500 GHz via a five-pole Debye model [4]. FDTD simulations (CST Studio Suite) are shown in Fig. 2 for a lateral plane wave impinging the WHB from the left side show moderate absorption at 3 GHz, increasing sharply towards 25 GHz and shows distinct "hot spots" at 500 GHz, especially in the head, legs, and antennae. Of concern for potential hazard is that the bee's "ear" is situated at the antenna joint. The cuticle slightly shields fields below 40 GHz [5]. Maximal specific absorption rate (SAR) values occur at the cuticle surface, but the whole-body SAR – the value expressed under ICNIRP [6] exposure conditions amounts to 7,6 W/kg – surprisingly exceed the ICNIRP limits for the general public by nearly fourfold, suggesting these guidelines are not protective for bees.

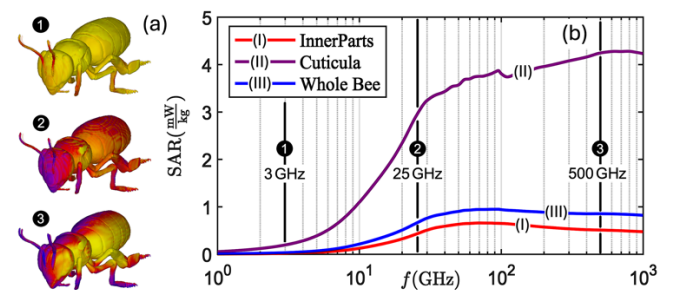


Fig. 2. Simulation results of the EM exposure of a honeybee (heterogeneous digital twin): (a) Volume density of the absorbed power for an EM wave incident laterally from the left (with a radiation power density of 1.33 mW/m²) at frequencies of (1) 3 GHz, (2) 25 GHz, and (3) 500 GHz (light yellow: ~0.1 W/m³; red: ~1 W/m³; blue: ~3 W/m³). (b) Maximum value of the local specific absorption rate (SAR) distribution with respect to (I) all internal organs, (II) the chitin exoskeleton (cuticle), and (III) the entire bee body.

Although this numerical comparison is not entirely fair due to the vastly different reference volumes involving the proper definition of the SAR exposure limits, it is a key driver of our future "electromagnetic bee research".

III. OF BEES AND FLOWERS (AND HORNETS)

So far, our bee models have mainly been used to gain dosimetrically motivated insights into the interior of the body. Digital twins now open the possibility of deploying these models on a broader scale, allowing them to interact with a virtual local ecosystem, as illustrated in Fig. 3a. Our overarching goal is the continuous (24/7) monitoring of all interactions using fast millimeter-wave or THz frequency-modulated continuous-wave (FMCW) radar imaging, enabled by ultra-compact components and systems developed within the collaborative research framework aiming at mm-wave/THz technology [7].

One objective is to study interactions between pollinators – especially bees – and pests around a model plant. Changes in movement kinematics, for instance, may reveal environmental stressors such as electromagnetic fields. In addition, the "air traffic" at the entrance of a beehive will be monitored in real time using similar high-resolution radar systems. This kind of "checkpoint" is intended to detect and, if necessary, repel hornets, to quantify "cargo flows" based on bee payloads such as pollen or honey, and identify pests like the small Varroa mite [3] that attempt to enter the hive as "blind passengers".

The distinction between loaded and unloaded bees, hornets, and other actors is achieved by analyzing backscattered EM waves in the form of characteristic radargrams or radar cross-sections (RCS). These signatures were precisely measured using a bistatic THz time-domain spectroscopy system on 3D-printed "bee dummies" in the frequency range from 100 GHz to 1 THz [3,4]. Training AI-based classification systems, however, requires large datasets that can be generated efficiently only through electromagnetic simulations. For this purpose, the highly detailed digital twin of the WHB shown in Fig. 3b enables realistic RCS calculations, exemplified at 100 GHz in Fig. 3c.

Both monitoring scenarios will initially be tested in a virtual ecosystem composed of interconnected digital twins, which – through *multiscale* numerical approaches – can also represent larger spatial relationships. How successfully these research visions can be realized will become clear in the near future and will ultimately depend on the honeybees themselves – both the real ones and their digital counterparts.

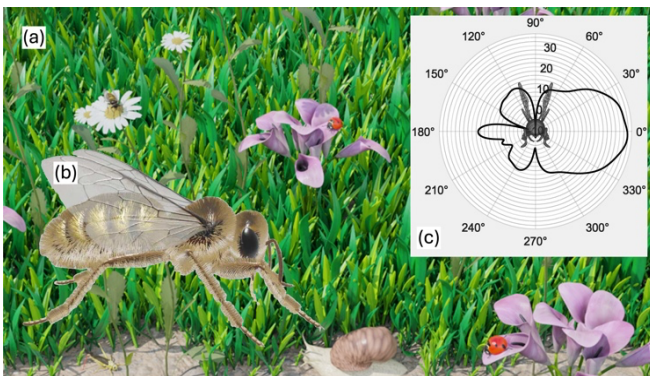


Fig. 3. (a) Complex digital twin of a local ecosystem: In the busy scene (Wimmelbild), in addition to the virtual models of the various grasses and two flower species, models of a bee, two ladybugs, and a snail are also visible. (b) Extended digital twin of the honeybee (shown enlarged) with a much more detailed external morphology for the numerical determination of realistic radar cross-sections (RCS). (c) RCS at a frequency of 100 GHz for a EM plane wave incident from the right side of the image.

IV. CONCLUDING REMARKS

We have shown that digital twins are essential tools for estimating radargrams and RCSs of WHBs and other insects in mm-wave/THz radar entomology within compact plant–pollinator–pest ecosystems. They may also enable continuous 24/7 monitoring of traffic at beehive entrances and even within hives in multistatic or harmonic radar scenarios. Furthermore, digital twins have proven valuable for projecting external EM exposure conditions onto the bee's fine-grained internal anatomy within an EM microdosimetry framework. Hence, digital twins serve a threefold purpose: (i) they can be viewed as sophisticated sensor systems that support the differentiation of insects based on their morphology and behavioral kinetics; (ii) they represent the only means of probing electromagnetic interactions within the different compartments of the bee; and (iii) thus function as epistemic engines, enabling us to address complex bio-electromagnetic questions in our research with greater reliability.

ACKNOWLEDGMENT

This research is partially funded by the Deutsche Forschungsgemeinschaft (DFG) through *CRC/TRR 196 MARIE* (Project-ID 287022738) under project M03, and supported in parts by the Ministry of Culture and Science of the State of North Rhine-Westphalia (MKW NRW) through project *terahertz.NRW*, as well as in parts by the Federal Ministry of Education and Research, Germany (BMBF) through the *6GEM* research hub under funding reference 16KISK039.

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SENSORICA 2026 / June 18-19, 2026



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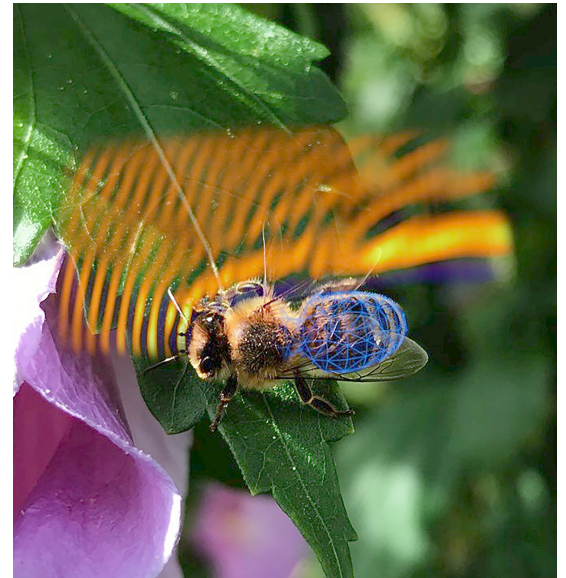
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Introduction



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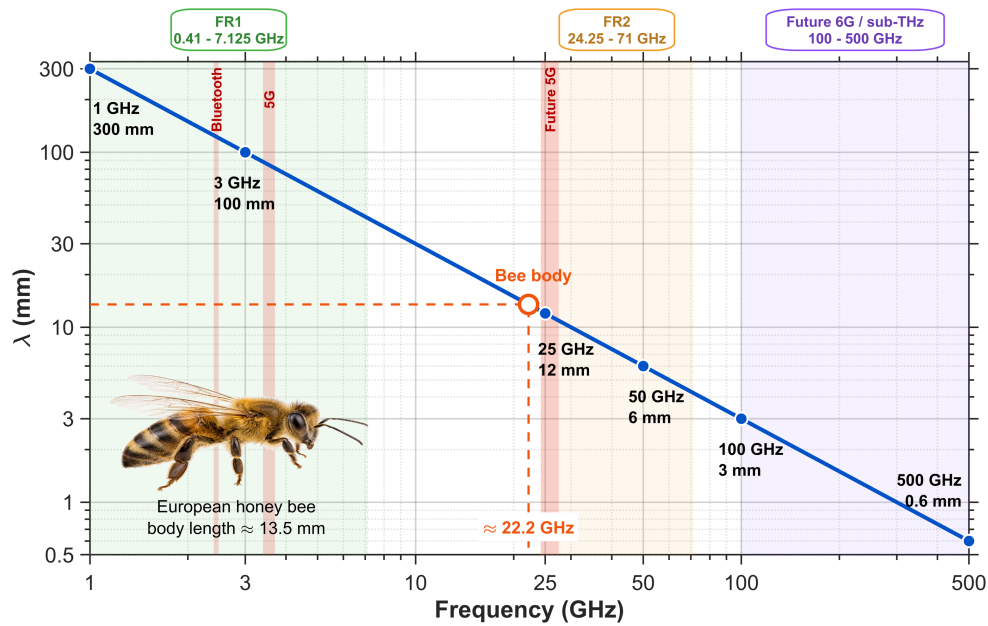
Why THz waves?

- Operating at frequencies in the THz range allows for a radical miniaturization of e.g. radar systems (including the antennas!) on a chip (footprint ~ few mm²).
- Such tiny THz technology allows for a continuous 24/7 (and practically undetectable) monitoring of small, local plant-insect-ecosystems at a high spatial resolution.
- Plants: Monitoring internal states and estimation of stress with respect to e.g. contamination and pests.
- Insects: Discerning the «players» in this ecosystem & investigating their exposure to surrounding EM fields.
- Plant and insect monitoring with THz waves is an ongoing venture.



Insect monitoring

The importance



Agenda



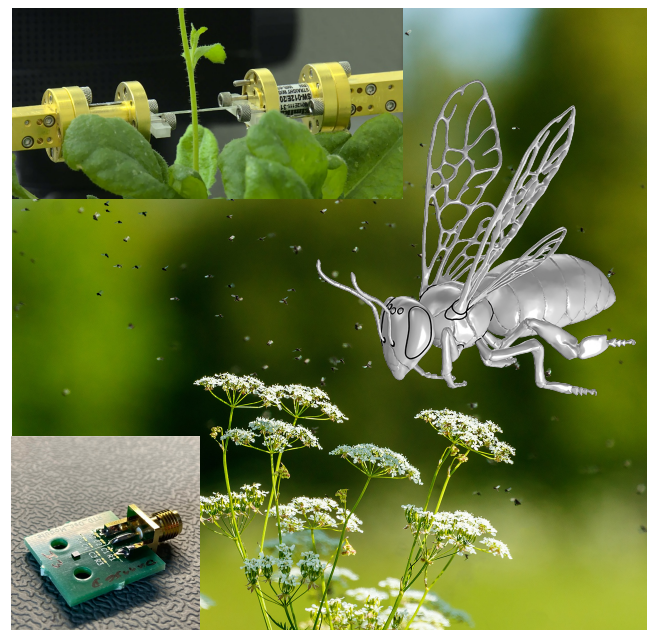
Bee monitoring

- Analysis of THz bee radar cross-sections (RCSs).
- Experimental setups and radar measurements.

Bee exposure

- Bee morphology and digital twins.
- Material characterization of bee parts.
- EM energy uptake and SAR in bees.

Conclusion & Outlook





Insect & Bee Monitoring



Insect monitoring

Reports and paper reviews



Bee monitoring

- Goal #1: Using a mm-wave/THz FMCW MIMO radar to monitor the plant-pollinator-pest interaction and behavior in this very local ecosystem (biom).
- Goal #2: Bee hive checkpoint identifying intruders (e.g. hornets, varroa mites) and analyzing aggregated mass flows (bees, pollen, nectar).
- Differentiation: Based on RCS, velocity vectors, statistics.

Bee exposure

- Goal #1: Are commonly known electromagnetic (EM) exposure limits (SAR) applicable to insects & bees?
- Goal #2: What are potential impacts on bee health & behavior?
- Analysis is based on computational microdosimetry at digital twins.

Sci. Rep., vol. 15, article no. 10638, pp. 1-23, March 27, 2025, doi: [10.1038/s41598-025-91630-8](https://doi.org/10.1038/s41598-025-91630-8).

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scientific reports

2025

OPEN

Perspectives on terahertz honey bee sensing

Andreas Prokscha^{1,2,3}, Fawad Sheikh^{4,5,6}, Mandana Jalali⁷, Pieter-Jan De Boose⁸, Elise De Borre⁹, Vera Jeladze^{10,11}, Felipe Oliveira Ribeiro¹², David Toribio Canvajal¹³, Jan Taru Svejda¹⁴, Tobias Kubiczek¹⁵, Basem Aqlan¹⁶, Pooya Alibeiglou¹⁷, Enes Mutlu¹⁸, Jonas Watermann¹⁹, Jonathan Abts²⁰, Robin Kress²¹, Christian Preuss²², Simone Clochiatti²³, Livia Wiedau²⁴, Nils G. Weimann²⁵, Jan C. Balzer²⁶, Arno Thielens²⁷, Thomas Kaiser²⁸ & Daniel Erni²⁹

2023

Towards Continuous Real-Time Plant and Insect Monitoring by Miniaturized THz Systems

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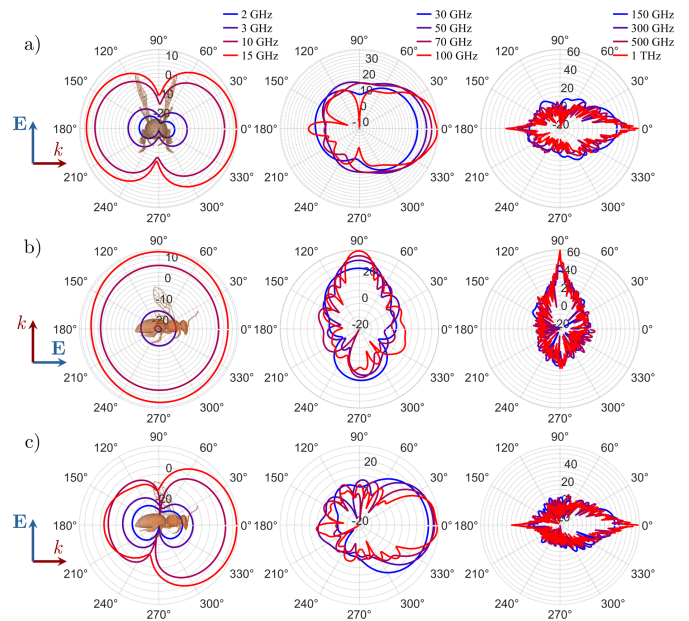
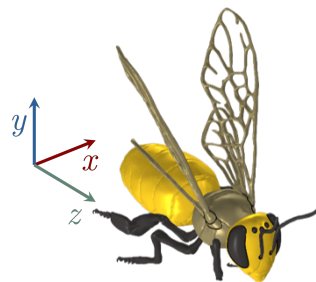
(Regular Paper)

Insect monitoring

Bee Radar Cross Sections (RCSs)

Bee monitoring

- RCSs of the anatomically accurate digital twin of western honey bees, under all possible excitation polarizations and in a broadband frequency range of 1 GHz – 1THz
- The RCSs will be used to train a supervised machine learning algorithm for classifying western honey bees from other species such as hornets and wild bees.



Insect & Bee Exposure



THz bee exposure

EM microdosimetry in highly complex body morphologies



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BAFU insect exposure study (Switzerland)

- Literature study: (132 journal publication)
 - LF: 0–100 kHz $n = 76$
 - HF: 100 kHz–6 GHz $n = 47$
 - VHF: 6 GHz–300 GHz $n = 9$
- Evidence level above 6 GHz weak; urgent need for research!
- mm-wave/THz: Possibility of resonant EM energy uptake.

Bee morphology

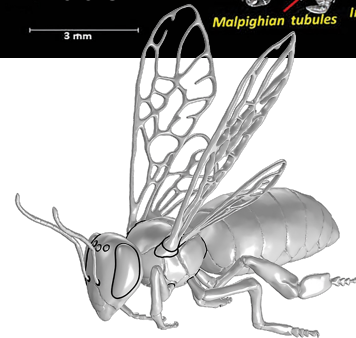
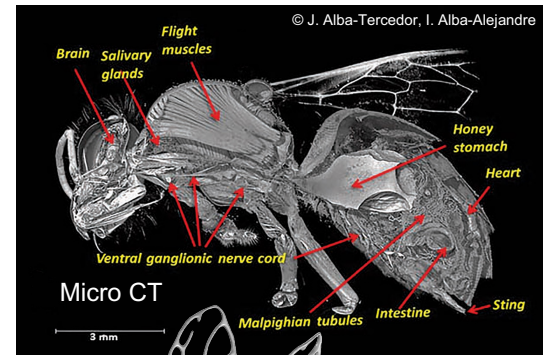
- Very complex honey bee morphology!
- Digital twin-based EM microdosimetry needed.

BAFU: (Swiss)
Federal Office for
the Environment.

Wirkung von nichtionisierender
Strahlung (NIS) auf Arthropoden

Im Auftrag des Bundesamts für Umwelt (BAFU)
18.08.2022

M. Mulet, T. Kroeber, M. Gossner, and J. Froehlich, "Wirkung von nichtionisierender Strahlung (NIS) auf Arthropoden," report commissioned by the **Bundesamts für Umwelt (BAFU)**, Neuenburg, Switzerland, 2022.

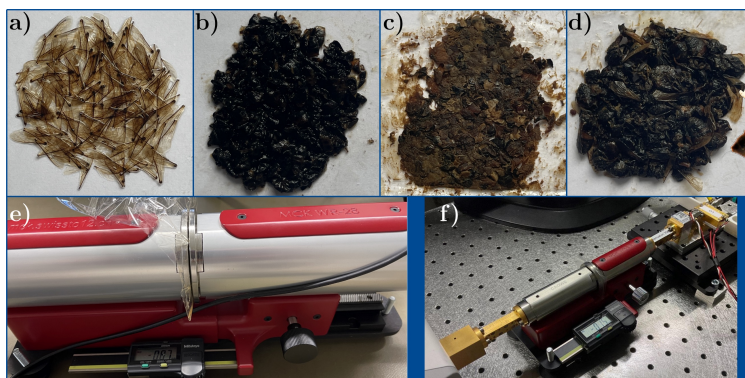


Material characterization of «bee components»

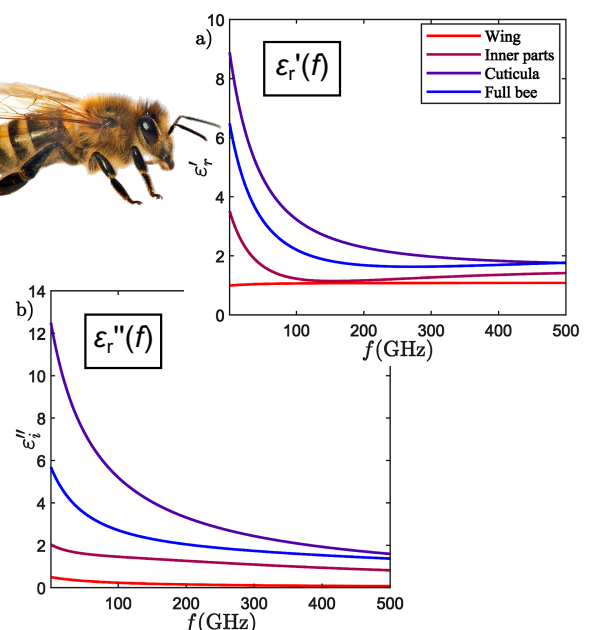
Dissection of bees for specific material models



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- Bee parts: (a) wing / (b) cuticle / (c) internal organs / (d) whole bee
- Measurements: Transmission/reflection setup (SWISSSto12) for the K_a band (26.5–40 GHz) and D band (110–170 GHz).
- Dielectric function: 5-pole Debye model allows for extrapolation to the frequency range of 1-500 GHz.

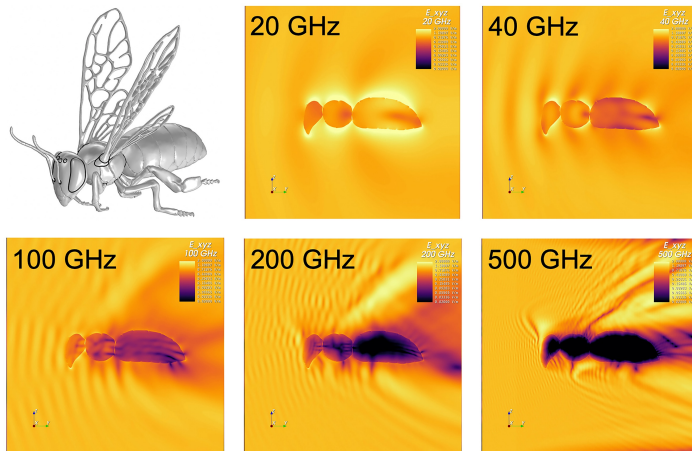


A first exposure analysis using digital twins

Bee as a scatterer of THz waves

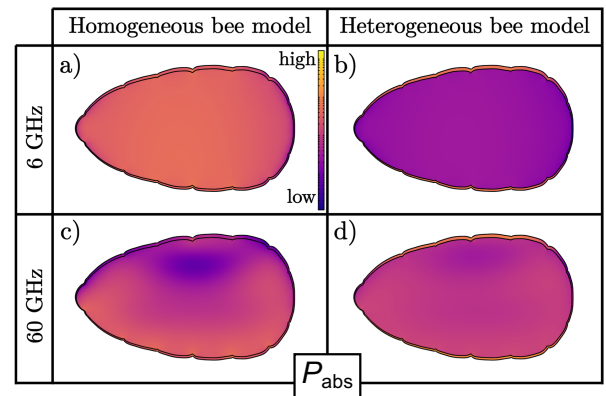


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- Electromagnetic 3D-FDTD simulation on a homogeneous bee model (frontal illumination of a digital twin).
- Significant penetration behavior of the electric field ≤ 40 GHz.

- Potential effects can only be studied in detail using a bee model with anatomically modeled organs (heterogeneous digital twin).
- Does the cuticle (chitin armor) have a shielding effect (right column)?



Energy uptake and SAR in bees

Microdosimetry with respect to power loss density

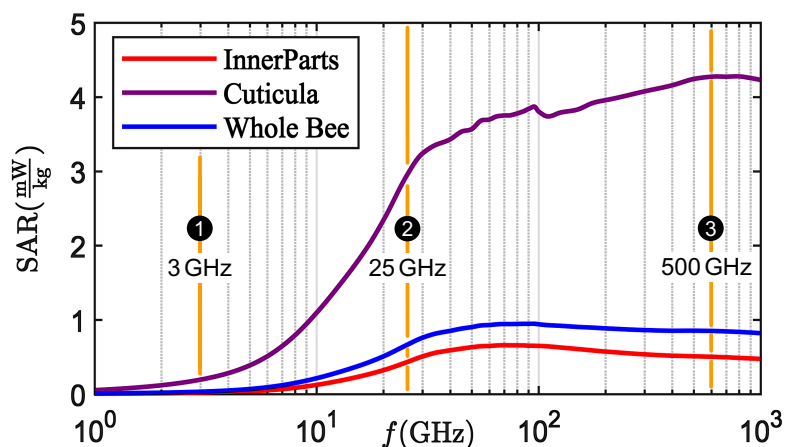
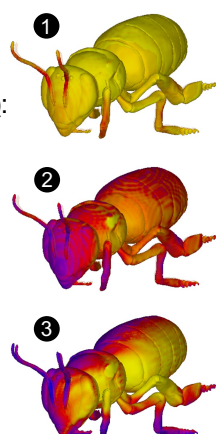
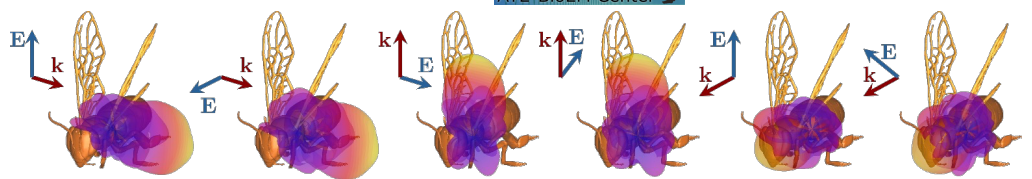


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Specific absorption rate

$$SAR = \frac{\sigma |E|^2}{\rho}$$

- Exposure according P_1 .
- Volumetric loss (bee figures):
 blue: $\sim 3 \text{ W/m}^3$
 red: $\sim 1 \text{ W/m}^3$
 yellow: $< 0.1 \text{ W/m}^3$
- Cuticle exhibits largest local SAR value $\sim 4 \text{ mW/Kg}$ (ICNIRP scaled: $\sim 7.6 \text{ W/Kg}$)
- ICNIRP exposure limit in public: $SAR_{10g} = 2 \text{ W/Kg}$



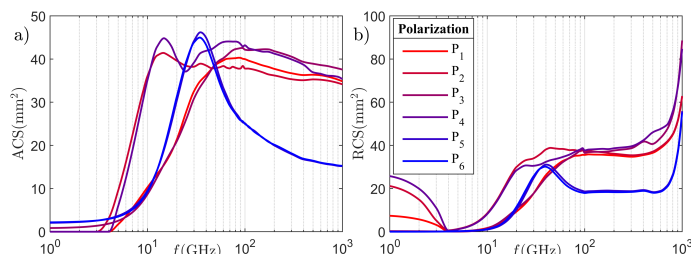
Energy uptake and SAR in bees

Microdosimetry with respect to power loss density



Power loss density

- Power loss density is highly frequency dependent.



f [GHz]	ICNIRP range / assumption	S_{inc} [W m ⁻²]
1	0.4–2 GHz	22.05
3	2–6 GHz	40.00
25	6–300 GHz	31.11
100	6–300 GHz	24.34
500	Outside ICNIRP 2020; using 300 GHz level	20.00

1 GHz

100 GHz

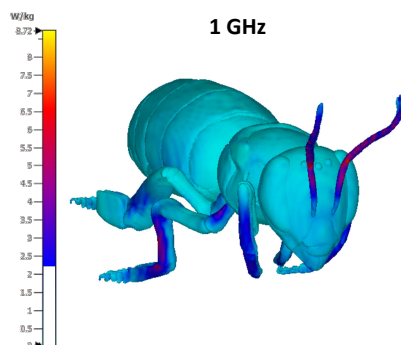


Energy uptake and SAR in bees

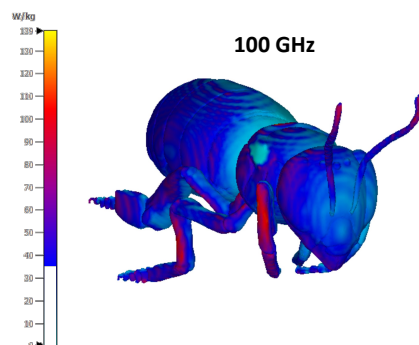
Microdosimetry with respect to specific absorption rate



Specific Absorption Rate (SAR)

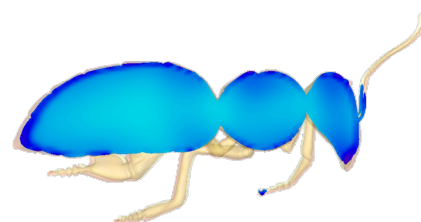


1 GHz



100 GHz

100 GHz – Lateral view



Energy uptake and SAR in bees

Microdosimetry with respect to temperature rise



Temperature profile

- Temperature increase according P_1 .
- Temperature increase in more uniform through the bee body compared to SAR and Power loss density
- Temperature increase up to 100 GHz is still not so high that would result in potential biological damages.



Summary & Outlook



Summary & Outlook



Conclusions

- Even if we have shown pretty nice and outstanding results:
Our interdisciplinary research on THz plant and insect monitoring is still evolving (it's still engineering research).
- From an engineering perspective the «players» in our ecosystem are quite challenging in terms of stochastic variations in shape, morphology, constituents, movements, and behavior.
- The radical miniaturization in THz engineering enables a very close (and hidden) view into the local ecosystems with the interesting possibility of «participant observation».

Outlook

- We must collaborate way more closely with plant biologists, entomologists, neurobiologists, ethologists, and bee keepers.



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Thanks!

Questions?

