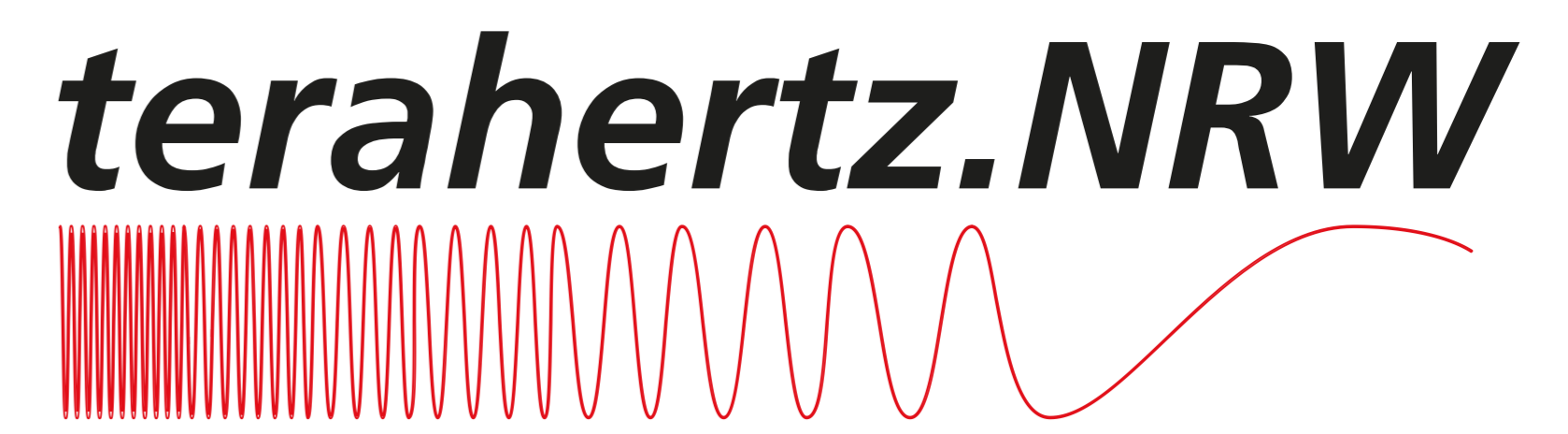


Perspectives on Terahertz Honey Bee Sensing



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This work [1]:

- Characterized dielectric properties of honey bee body parts up to 500 GHz
 - Introduced, for the first time, a heterogeneous body model based on detailed material characterization of European honey bees (*Apis mellifera*)
 - Exploring dosimetry at 300 GHz
 - Compared real honey bees with 3D-printed honey bee models to analyze scattering behavior and exploring the radar cross-section (RCS)
- 3D-printed bees turned out to be promising surrogates for real insects in THz measurements
- Captured anatomical detail through high-resolution THz imaging
 - Investigated the correlation between bee model pose and THz wave polarization

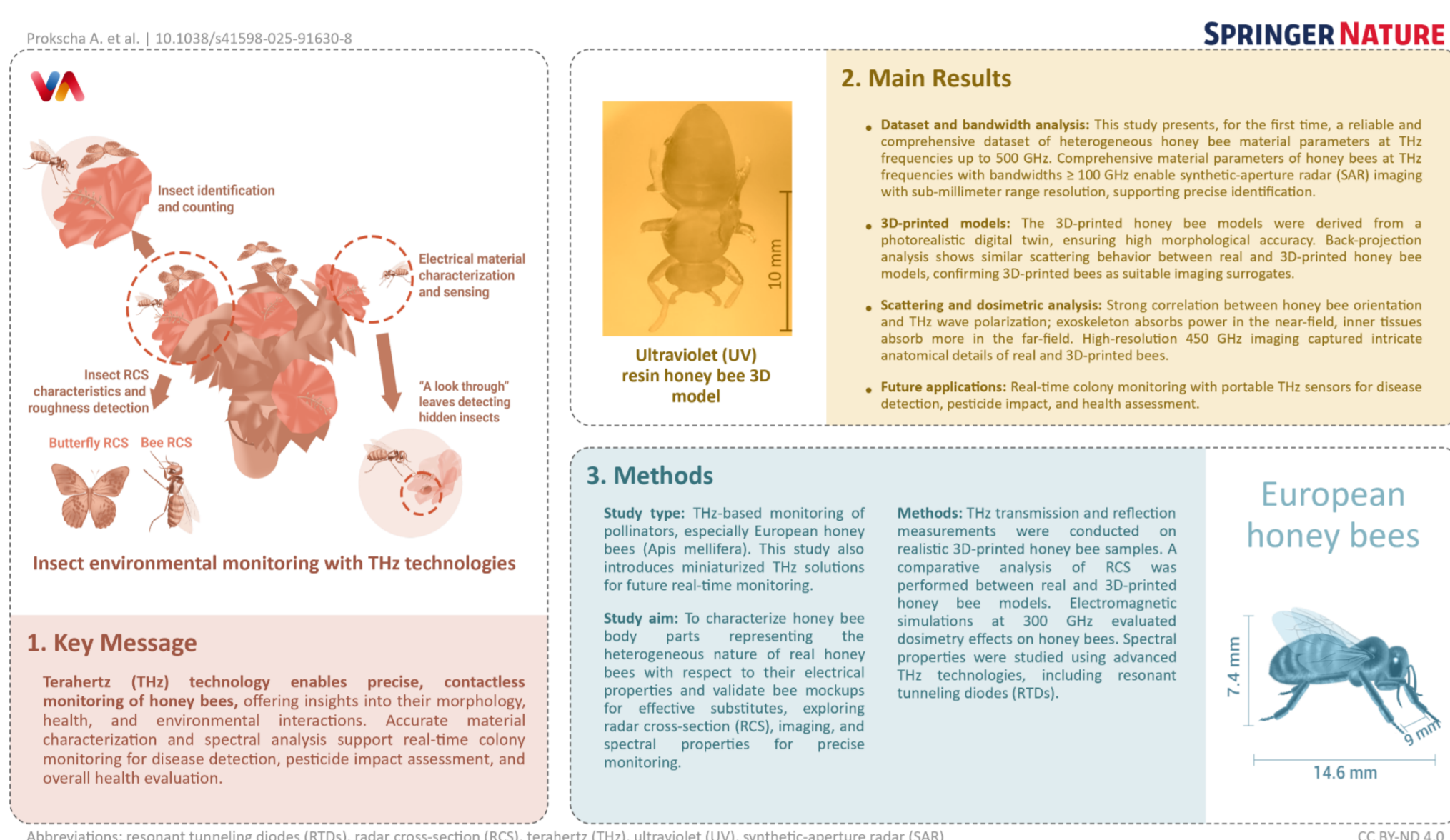


Figure 1, Visual abstract of this work.

Heterogeneous Honey Bee Model up to 500 GHz

- SwissTo12 MCKs measured in the K_a -band and D-band
- Test samples were aggregated to form planar and dense flat material probes for wings, cuticula, inner parts and homogenized total bees
- Note:** Honey bees were collected post-mortem by a beekeeper and preserved in 70% ethanol solution to prevent dehydration

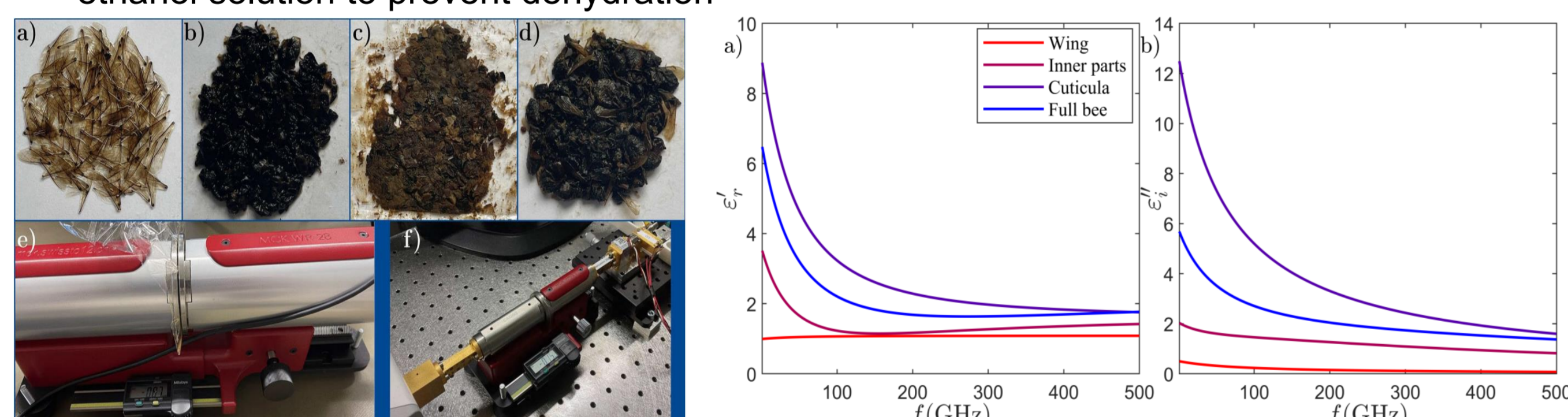


Figure 2, Varieties of bees and their respective parts used as measurement samples: (a) wings, (b) cuticula, (c) inner parts, (d) full bee. Displayed in (e) is the SWISSTo12 MCK system for the K_a -band, accompanied by the cling foil packaging, while (f) showcases the same system for the D-band, featuring the two frequency extenders and accompanied by cling foil packaging.

Figure 3, The retrieved complex permittivity of European honey bees: (a) real part, and (b) imaginary part (right).

- 5-pole Debye model:

$$\epsilon = \epsilon_{\infty} + \sum_{i=1}^5 \frac{\Delta\epsilon_i}{1 + j\omega\tau_i} + \frac{\sigma_s}{j\omega\epsilon_0}$$

Table 1, The coefficients of the fitted 5-pole Debye model for the first five terms.

Bee parts	ϵ_{∞}	$\Delta\epsilon_1$	$\Delta\epsilon_2$	$\Delta\epsilon_3$	$\Delta\epsilon_4$	$\Delta\epsilon_5$	τ_1 (ps)	τ_2 (ps)	τ_3 (ps)	τ_4 (ns)	τ_5 (μ s)	σ_s (S/m)
Wing	9.65	956	976	828.5	94.5	790.5	625	999.5	241.5	66.5	340.5	15.6
Inner parts	1.61	452	737.5	899	694.5	983.5	3.5	63	266.5	299.5	761	15.6
Cuticula	1.59	373.5	10	70.5	288.5	773	416	232	894.5	79.5	698.5	15.6
Full bee	2.19	265.5	9.5	608	975.5	918.5	42	16.5	531.5	555.5	187	13.6

Additively Manufactured (AM) Honey Bee Mockups

- Two AM processes: Powder bed-based fusion with plastics and VAT photopolymerization (VPP)
- Powder of the material (polyamide 12/PA 12) melted by a heated nozzle and deposited layer by layer
- Lightcuring epoxy resin solidifies in a basin via a light source (laser or UV light)
- In the slicer software, a layer thickness of 25 μ m is chosen for both the bees and the separately produced wings
- These bees are manufactured with a set layer thickness of 0.1 mm

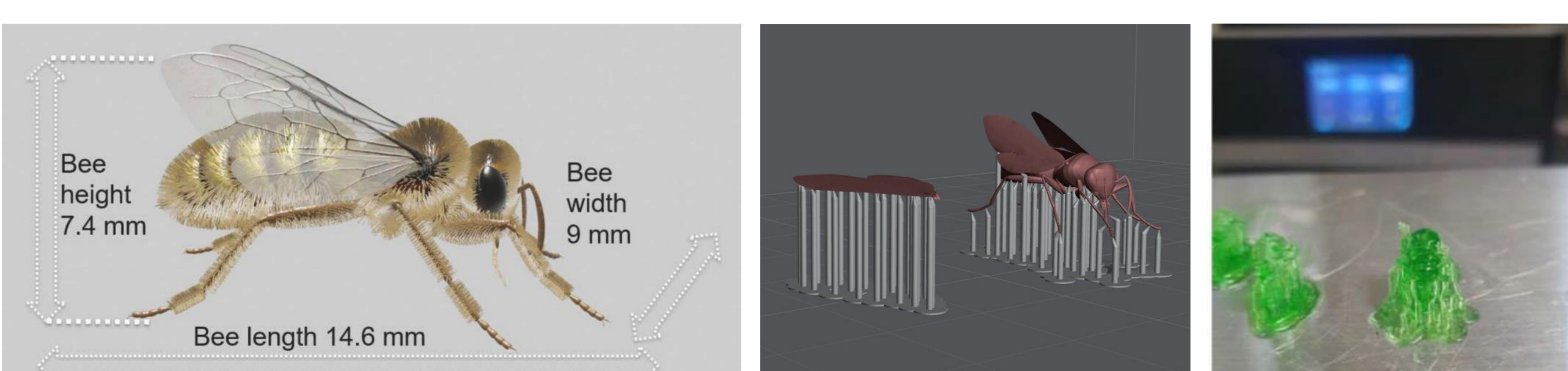


Figure 4, Illustration of the European honey bee digital twin used for AM and RCS measurements (left), bee model in virtual preparation space for AM side view (middle), and honey bee mockups in transparent green resins (right).

Experimental Imaging of Honey Bee Models with THz Time-Domain Spectroscopy (THz-TDS)

- Antennas arranged in a bistatic configuration with a 100 mm separation between the Tx and Rx
- Antennas positioned 200 mm away from the center of rotation. A parabolic mirror with a focal length of 50.8 mm collimates the divergent beam from Tx
- The honey bee models (UV resin and PA12) are rotated 360° in azimuth by a motor in 0.5° steps, maintaining a fixed elevation at 0°
- At each azimuthal position, 6000 THz-TDS traces are recorded and averaged
- Considering the rotation of the honey bees is carried out with fixed antennas, this approach aligns with inverse synthetic aperture radar (ISAR) imaging

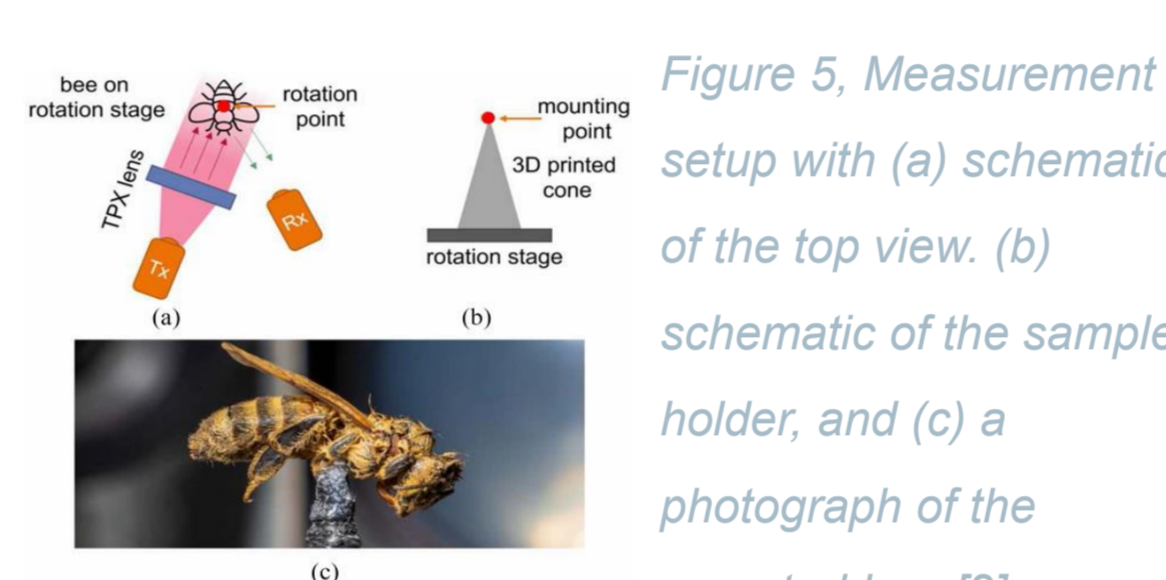


Figure 5, Measurement setup with (a) schematic of the top view, (b) schematic of the sample holder, and (c) a photograph of the mounted bee [2].

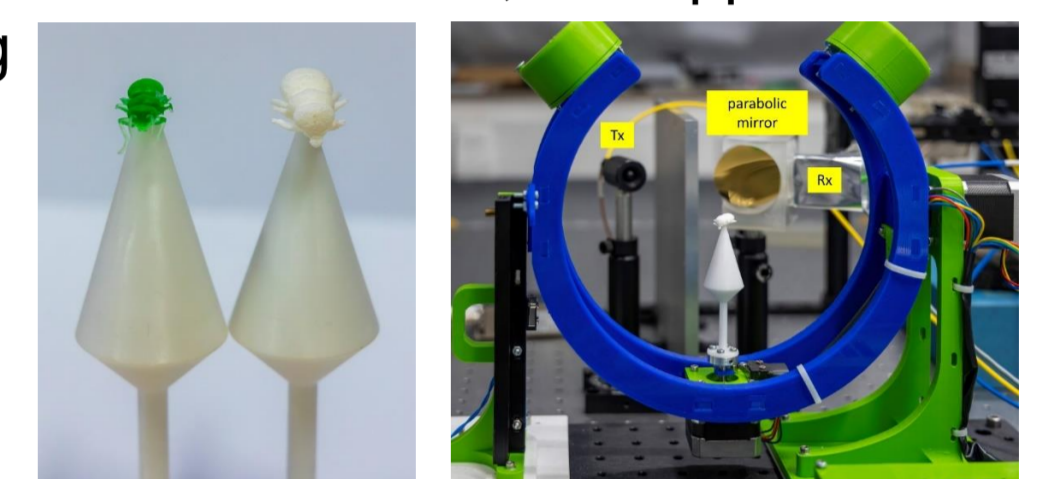


Figure 6, Measurement setup featuring (a) photo of honey bee models constructed with resin (green) and PA12 (white) materials mounted on the holder, and (b) side-view of the spherical THz-TDS system.

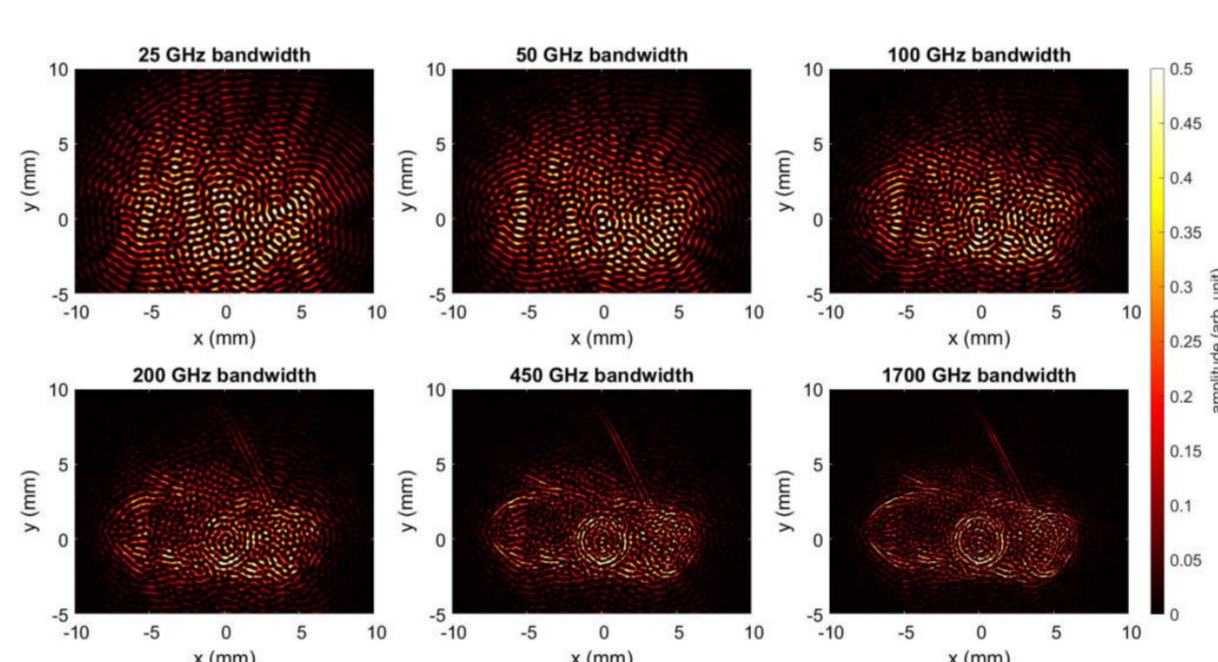


Figure 7, Back-projection of the measured THz-TDS data of a real honey bee. The start frequency for the back-projection is 300 GHz.

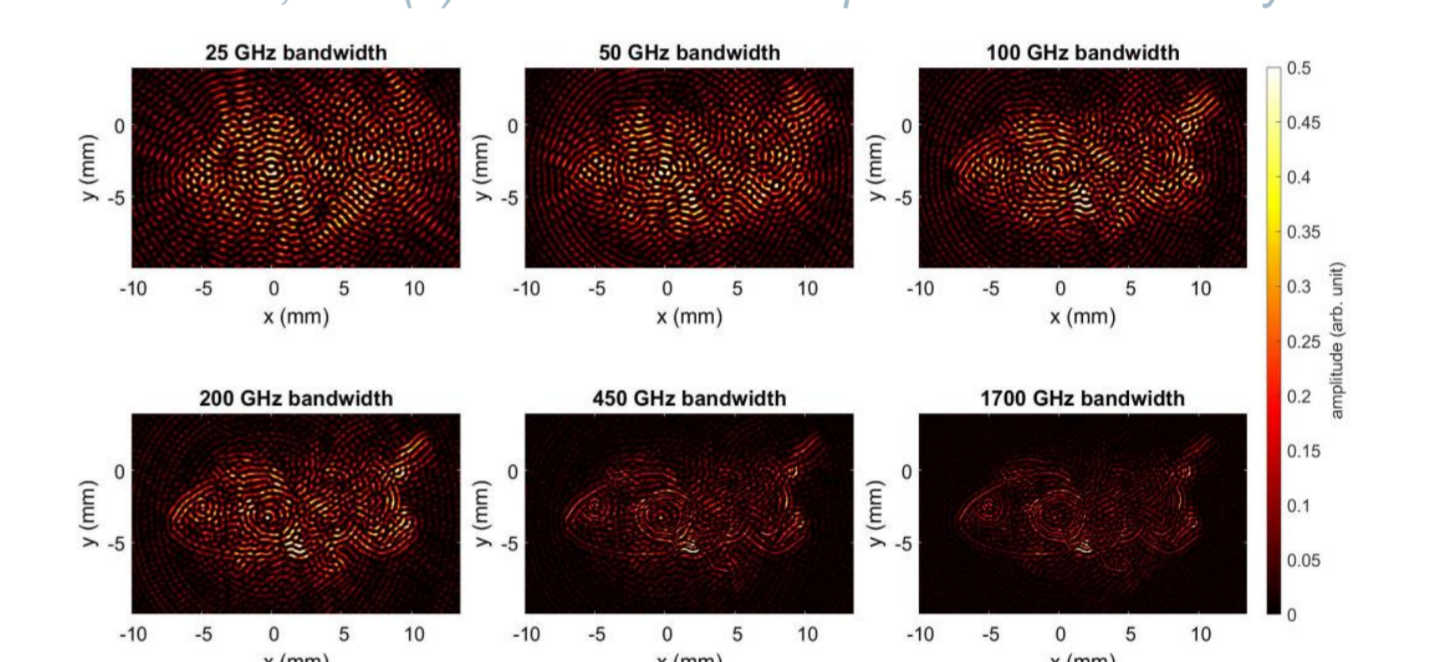


Figure 8, Back-projection of the measured THz-TDS data of a 3D-printed green honey bee. The start frequency for the back-projection is 300 GHz.

Scattered Power Measurements of Honey Bees using THz InP Resonant Tunneling Diode (RTD) Chips

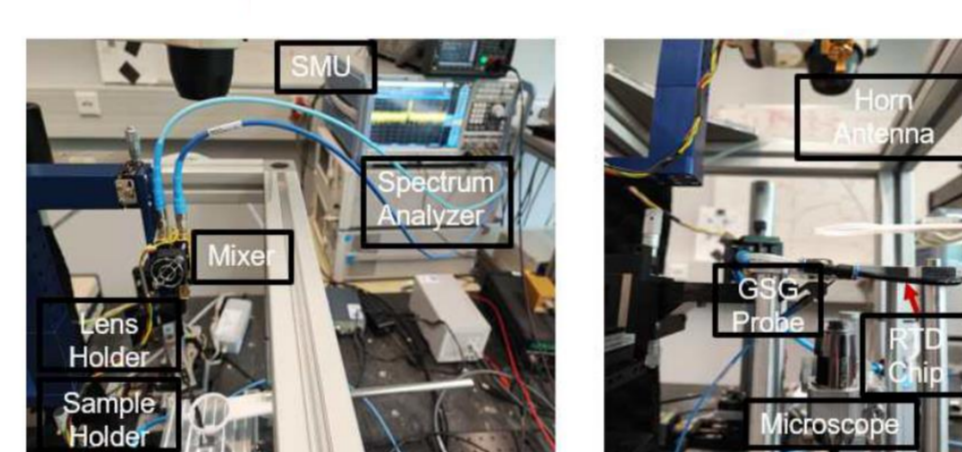


Figure 9, The measurement setup for the scattered power measurements with RTD oscillator chip integrated with slot antenna (a) top view and (b) side view.

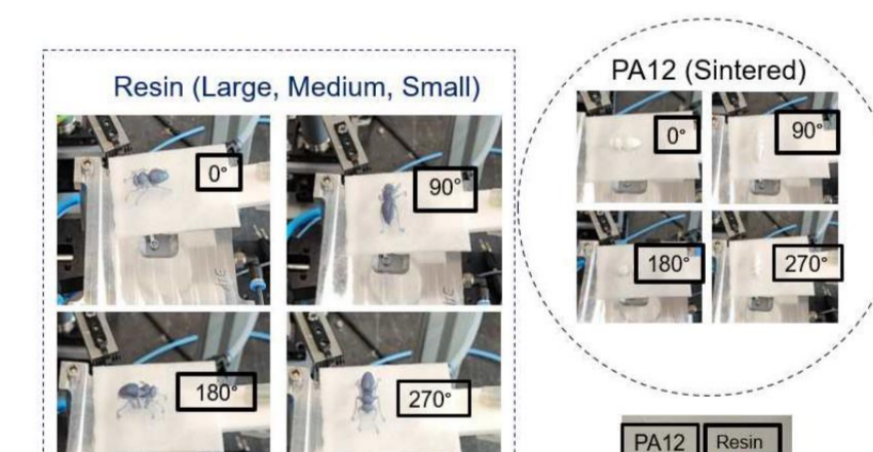


Figure 10, Positioning of AM honey bee models.

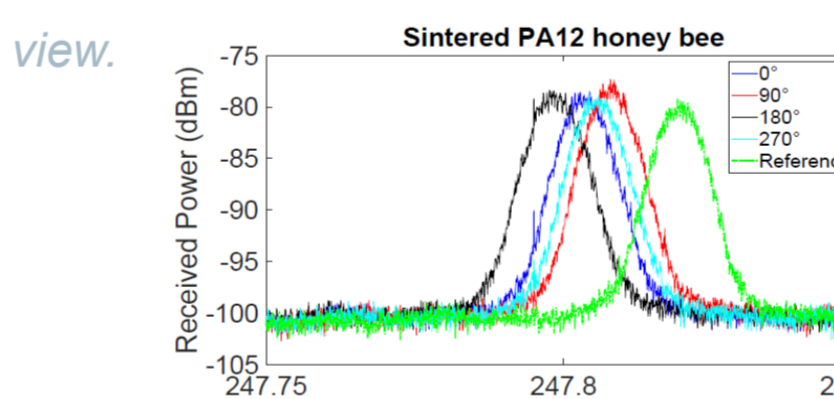


Figure 11, The recorded power spectra from the spectrum analyzer for two different samples and four different rotations: (a) powder bed-fused PA12 honey bee, (b) large resin honey bee.

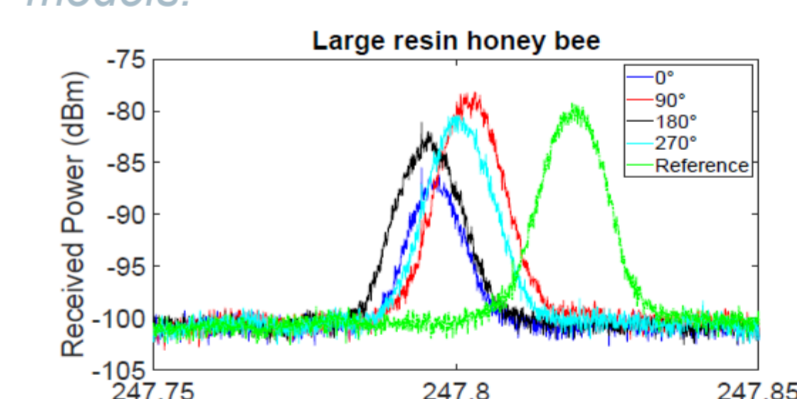


Figure 12, Absorbed power in four different tissues at 300 GHz for (a) four near-field configurations with 1 W input power, (b) corresponding far-field polarizations with an incident electric field strength of 1 V/m, (c) mid-sagittal and mid-coronal cross-sections of the electric field distribution at 1 cm separation distance from an orthogonally polarized dipole antenna that is fed an input power of 1 W at 300 GHz, (d) absorbed power in different tissues of the honey bee (with closed wings) for all considered far-field polarizations with an incident field strength of 1 V/m at 300 GHz.

- The recorded power spectrum around the peak frequency for different measured samples.
- Peak values are roughly the same for all rotations for PA12 models.
- Frequency shift to lower frequencies of around 10 to 20 MHz were observed.
- This effect can be correlated to the detuning of the main frequency of the RTD oscillator scattered peak power.

Terahertz Dosimetry at 300 GHz in European Honey Bees

- These simulations reveal that at very short distances (1 mm) from the antenna, the bee can absorb up to 26% of the input power into an antenna.
- In the near-field, the majority of the power is absorbed in the bee's exoskeleton.
- However, in the far-field, the inner tissues absorb a slightly higher relative fraction of the absorbed power. Observing compliance with the ICNIRP reference levels in the THz application, the maximally allowed far-field exposure of 10 W/m² corresponds to an average absorbed power of 0.29 mW into a honey bee worker.

References:
[1] A. Prokscha, F. Sheikh, M. Jalali, P. De Boose, E. De Borre, V. Jeladze, F. Oliveira Ribas, D. Toribio Carvajal, J. T. Svejda, T. Kubiczek, B. Aqlan, P. Alibeigloo, E. Mutlu, J. Watermann, J. Abts, R. Kress, C. Preuss, S. Clochiatti, L. Wiedau, N. G. Weimann, J. C. Balzer, A. Thielens, T. Kaiser, and D. Erni, "Perspectives on Terahertz Honey Bee Sensing," in Scientific Reports, vol. 15, March 2025, Art. no. 10638, doi: 10.1038/s41598-025-91630-8.
[2] F. Sheikh, A. Prokscha, A. Batra, D. Lesny, B. Salih, B. Slevert, M. Degen, A. Rennings, M. Jalali, J. T. Svejda, P. Alibeigloo, E. Mutlu, R. Kress, S. Clochiatti, K. Kolpatzek, T. Kubiczek, I. Ullmann, K. Root, F. Brix, U. Klöner, M. Vossiek, J. C. Balzer, N. G. Thielens, T. Kaiser, and D. Erni, "Towards Continuous Real-Time Plant and Insect Monitoring by Miniaturized THz Systems," in IEEE Journal of Microwaves, vol. 3, no. 3, pp. 913-937, July 2023, doi: 10.1109/JMW.2023.3278237.