The road to THz applications with societal relevance

A NOVEL TECHNOLOGY EXPLORING ITS SOCIETAL IMPACT

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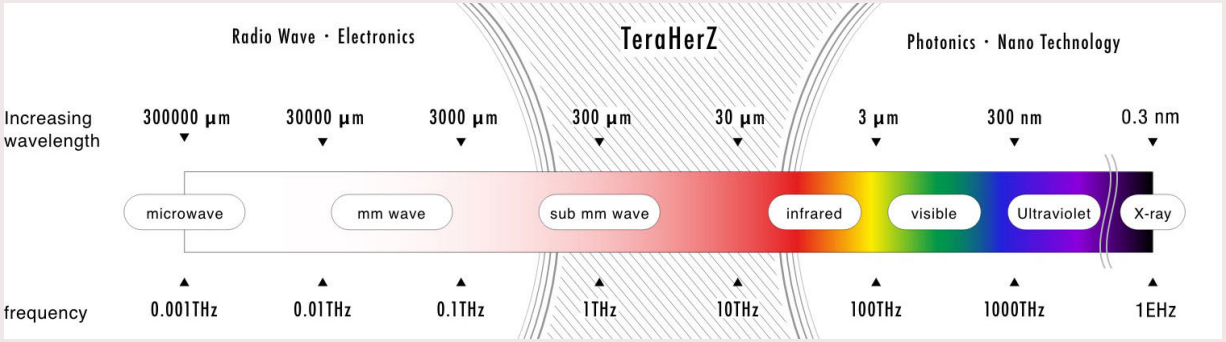
TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

Terahertz Technology and Hype



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A THz Killer application?

A dormant hope

– THz technology,

"should have a novel, innovative use with a business case strong enough to bring it into the industrial mainstream"

The road to THz applications with societal relevance – Optics & Photonics News, 16-18, November (2015)

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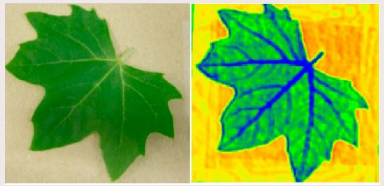
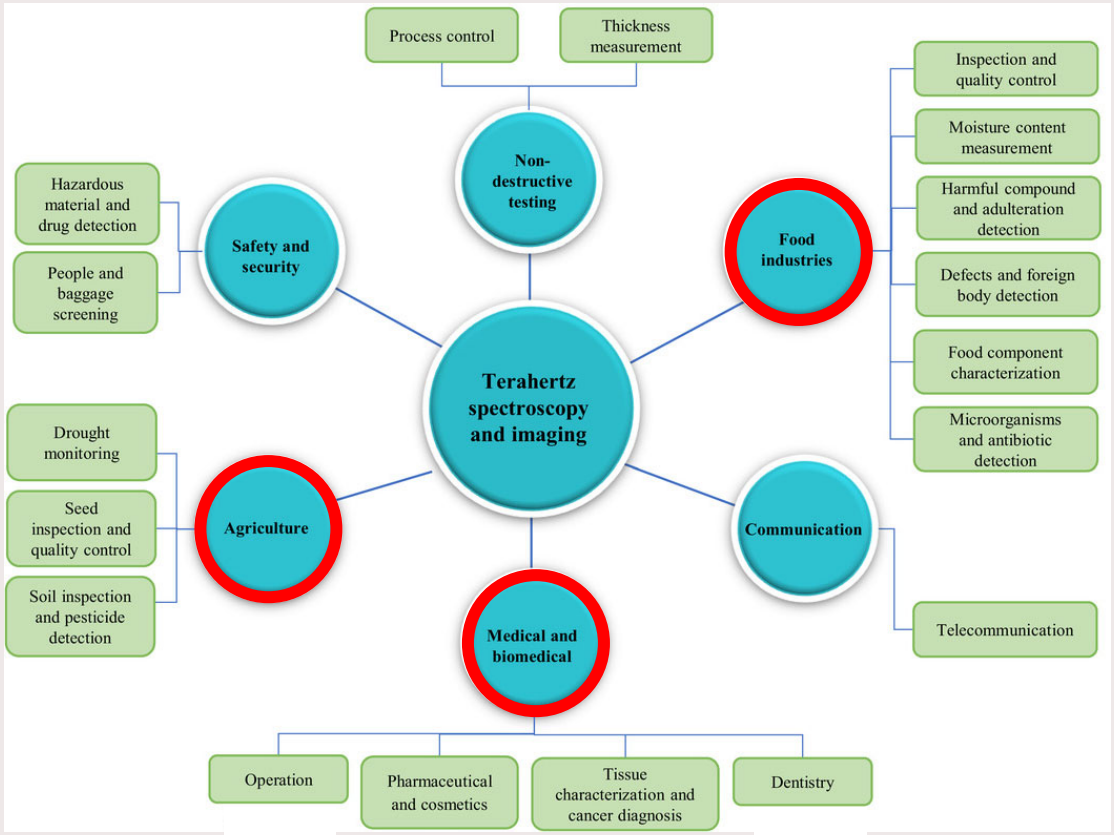
“Endless applications”

Suggestions / proof-of-concepts

- Medicine
- Food & agriculture





L. Afsah-Hejri et al., Vol.18, 2019, Comprehensive Reviews in Food Science and Food Safety

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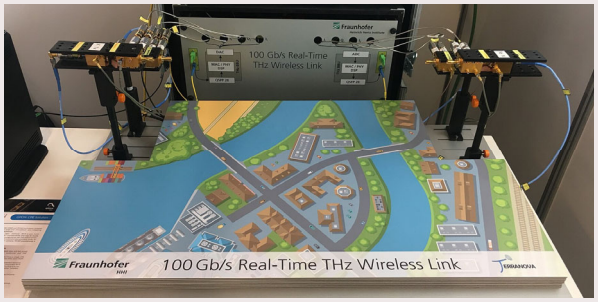
“Endless applications”

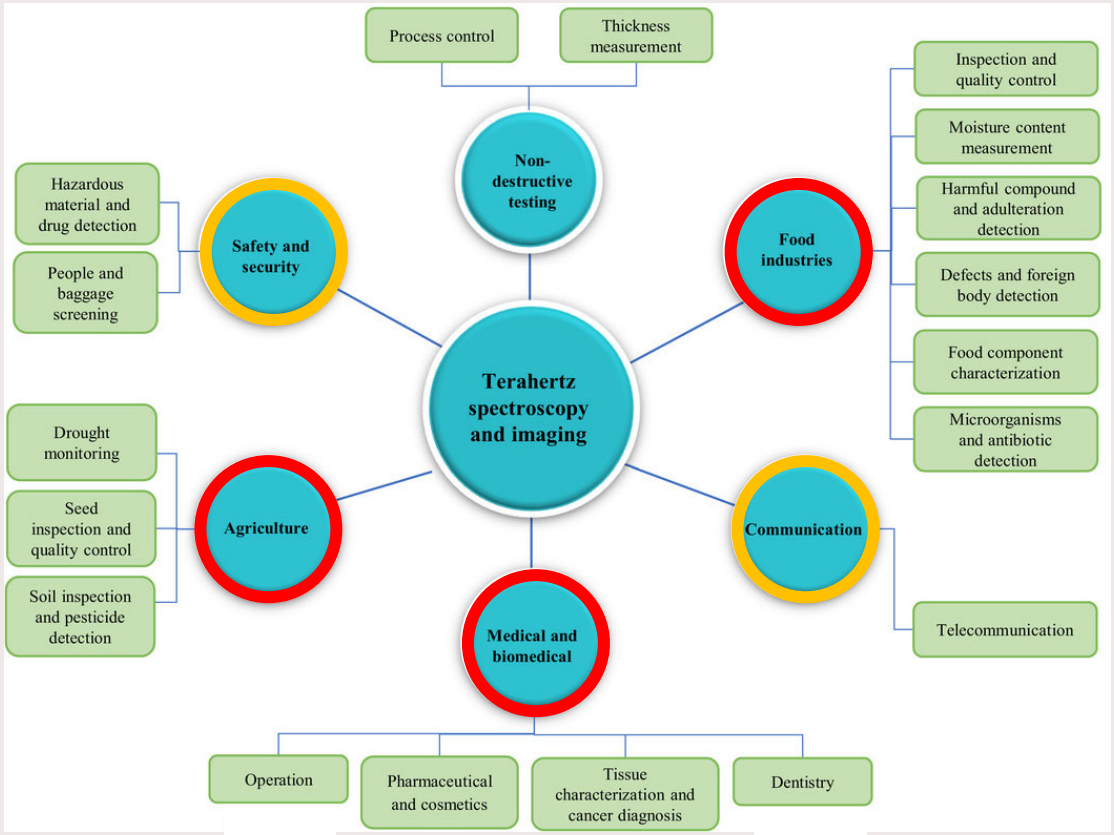
Suggestions / proof-of-concepts

- Medicine
- Food & agriculture

Lab demonstrations

- THz communication
- Art inspection





L. Afsah-Hejri et al., Vol.18, 2019, Comprehensive Reviews in Food Science and Food Safety

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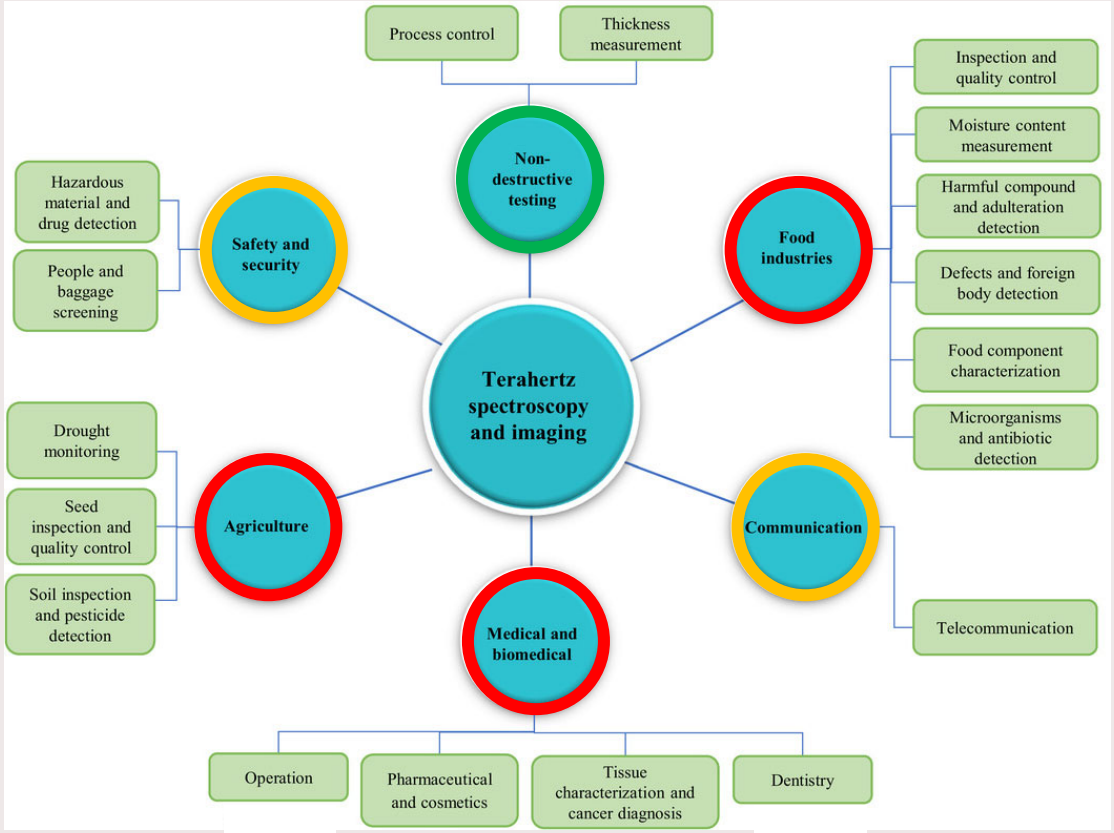
“Endless applications”

Suggestions / proof-of-concepts
- Medicine
- Food & agriculture

Lab demonstrations
- THz communication
- Art inspection

Field demonstrators / prototypes
- Semiconductor fault detection
- Thickness measurements
  - Coatings, sheets, etc.



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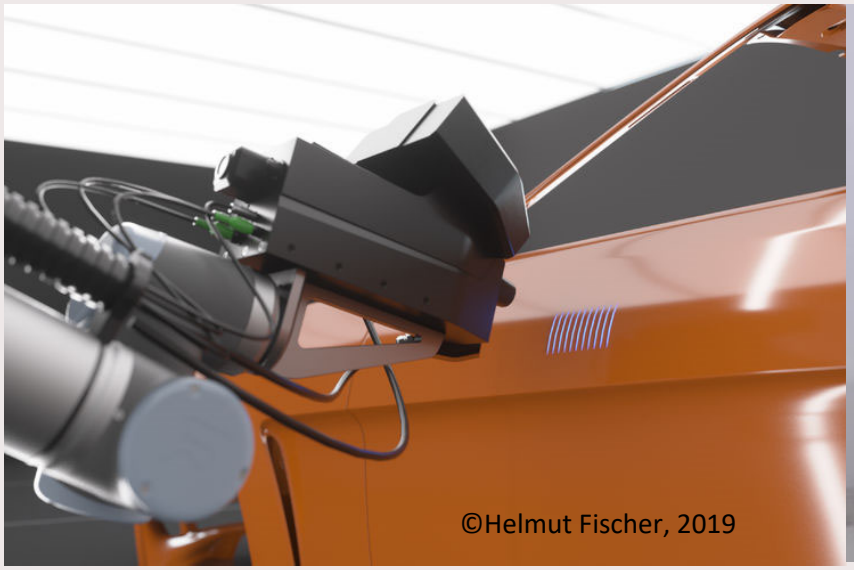
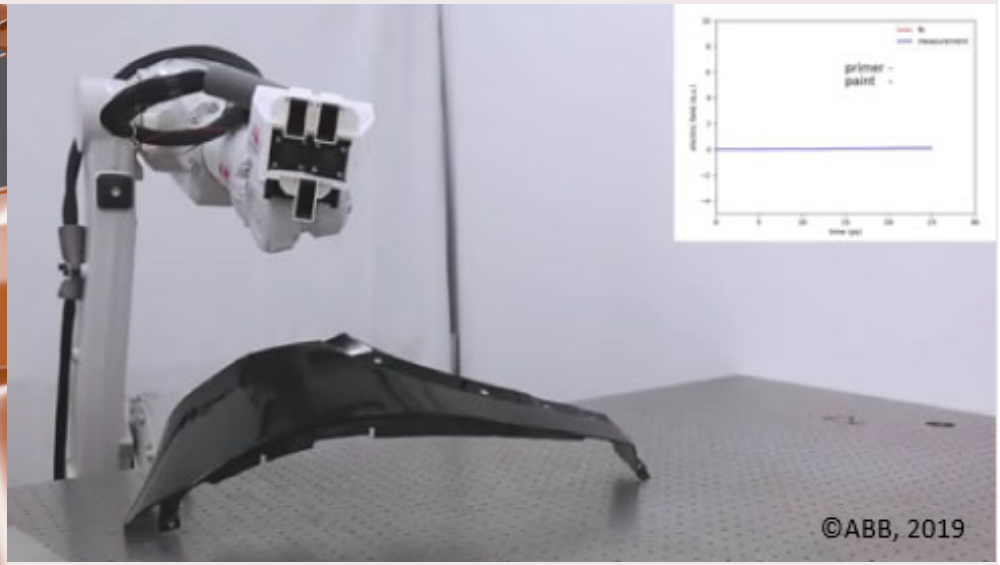
Terahertz-based early phase products

Coating sensor for the automotive industry





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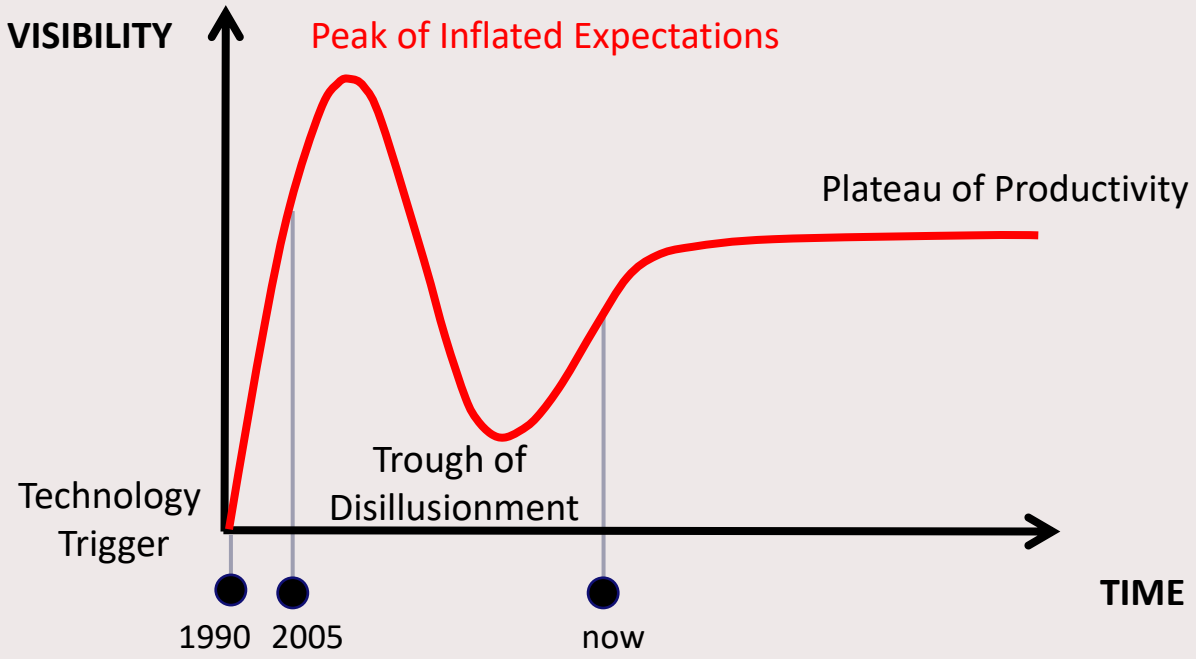
“Endless applications”

… a 2010 editorial quote in Nature Photonics



Why THz?

Feature	Unique benefit
Low photon energy	Not sufficient to make chemical changes
Sensitivity to water	Polar water is extremely absorptive, causing sensing benefits and challenges
Time-domain data aquisition	Phase and amplitude information: sensing thickness and spectral features
Spectral fingerprints	Characteristic resonances: characterizing materials

Why no THz?

Feature
Expensive (> 100k)
Unique benefit can often be circumvented with a different technology
Immature technological status
Bulky form factor

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Why are there so few mature applications?

Medicine

– Medical know-how is required, water is omnipresent, regulations

Agriculture

– Most studies are performed on not-realistic problem statements, sensing moisture remains academic

Communication

– Lacking problem description and goal of THz communication, as well as small/cheap devices

Food industries

– Mainly ideas exist that are compatible with small/cheap devices

Non-destructive testing

– Thickness determination most mature, price is an issue

- Dealing with water
- Lack of domain know-how
- Small/cheap devices required
- Signal processing
- TRL gap (3-5) development lacks

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A THz Killer application?

A dormant hope

– THz technology,

"should have a novel, innovative use with a business case strong enough to bring it into the industrial mainstream"

How to bring THz mainstream

– Combine state-of-the-art sensors & be cheaper

– Outperform the state-of-the-art

– Novel application with an innovative use

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Car paint shop

Why THz?

Feature
Low photon energy
Only technology that can measure wet paint
Sensitive to water
Time-domain aquisition
Form factor and price are no issue

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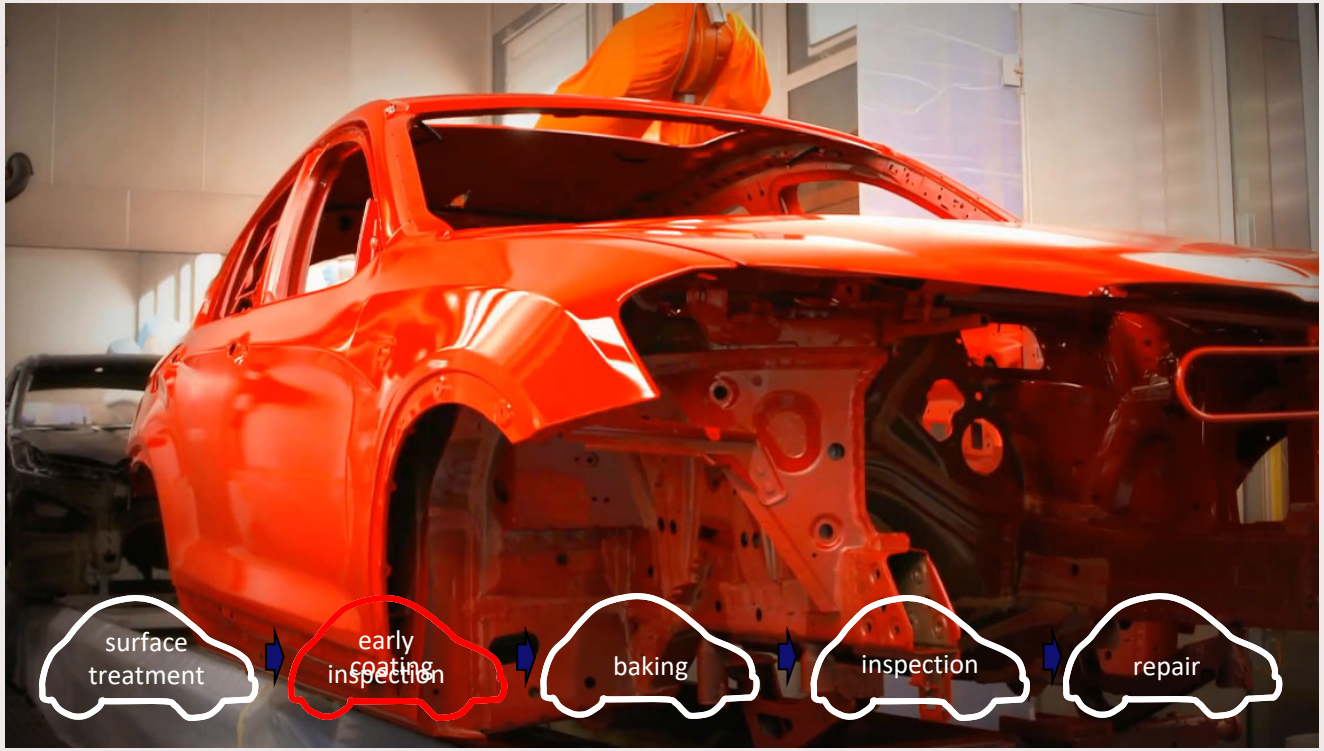
Car paint shop



- Only on few cars
- Error on curved surfaces
- No multilayer distinction
- No wet paint

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Development of a THz-based paint analyzer (TRL 1 – 4)

- Stage 1: Light-matter interaction
- Stage 2: Industrially/societally relevant parameters
- Stage 3: Signal processing to obtain parameters with desired accuracy

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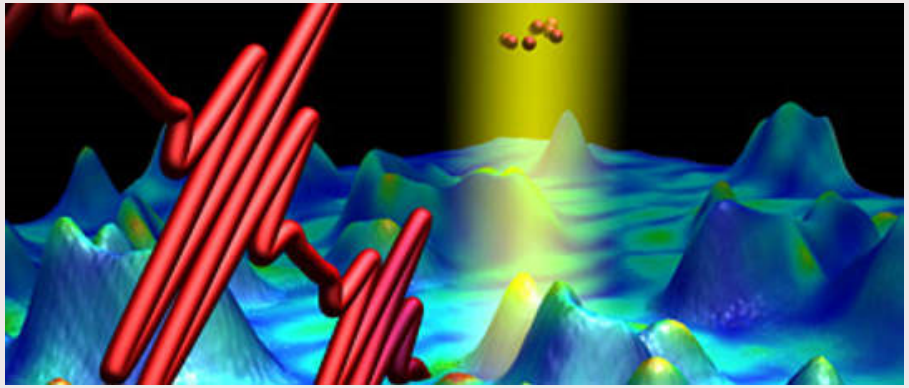
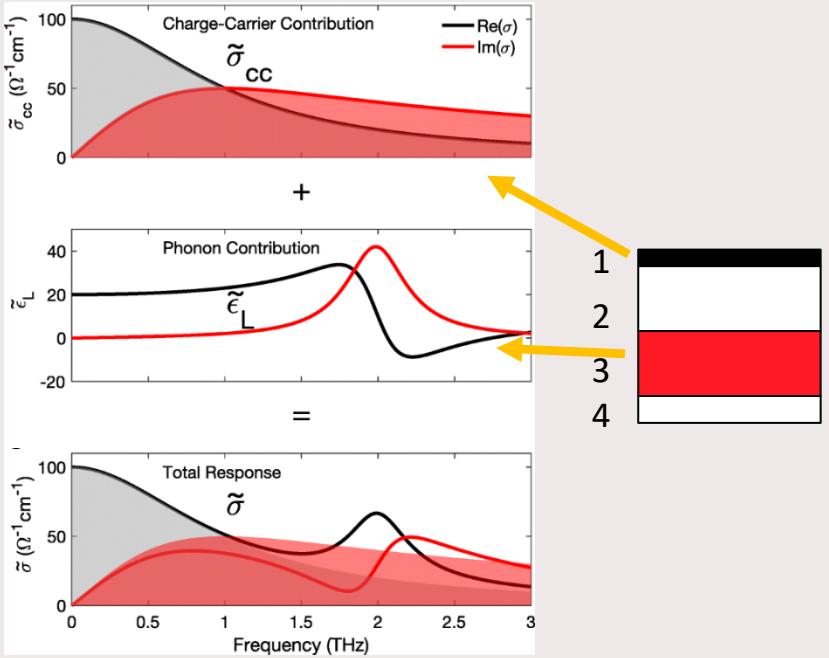
Light-matter interaction





A.M. Ulatowski et al, Journal of IRMMTHz 41, 1431 (2020)

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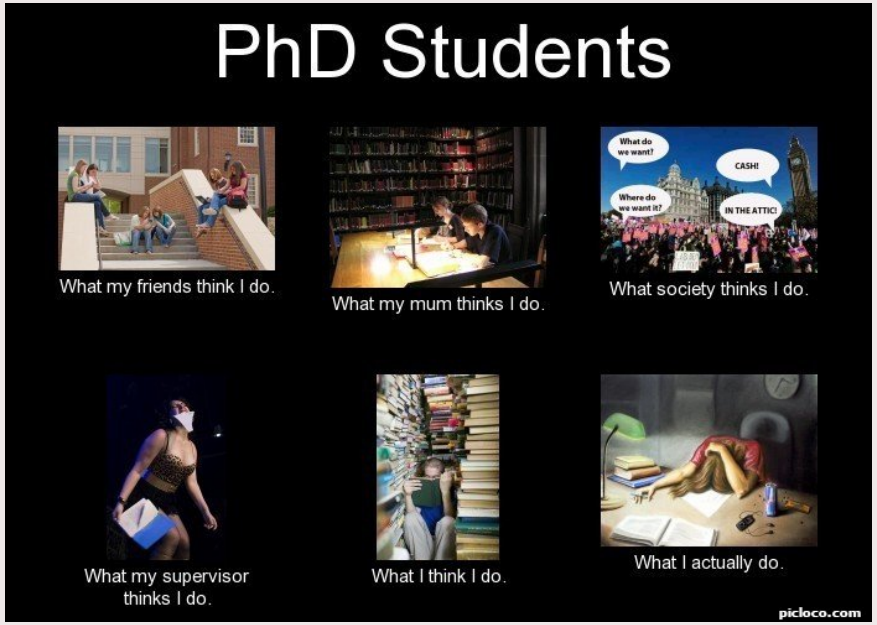
Industrially / societally relevant parameters



- Difficult to understand from outside the industry
  - What the academic researcher wants
  - What the paint shop manager wants
  - What the paint shop technician wants
  - What the customer wants
  - What actually needs to be done
- Even inside information may scatter a lot
- Doing field work is essential

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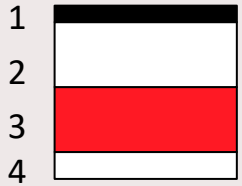
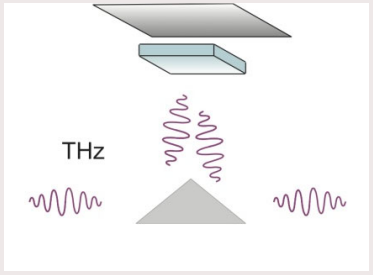
Model-based signal processing

Measurement design





- Reflection setup
- In ambient air
- In presence of humidity

Analysis model

$$E(\omega) = E_0 T_1 T_2 e^{i\left(\frac{n\omega}{c}\right)d} \times \ldots \left(1 + R_2^2 e^{2i\left(\frac{n\omega}{c}\right)d} + \cdots\right)$$

- Fresnel equations
- For multilayer system
- Include dispersion of $n(\omega)$

Fitting procedure

$E_r^{model}(\omega)$ matched to $E_r^{exp}(\omega)$

- Least-square algorithm
- Obtains unique set of $n(\omega)$ and d

Langmuir 30, 12748 (2014),
Optics Letters 39, 3853 (2014)

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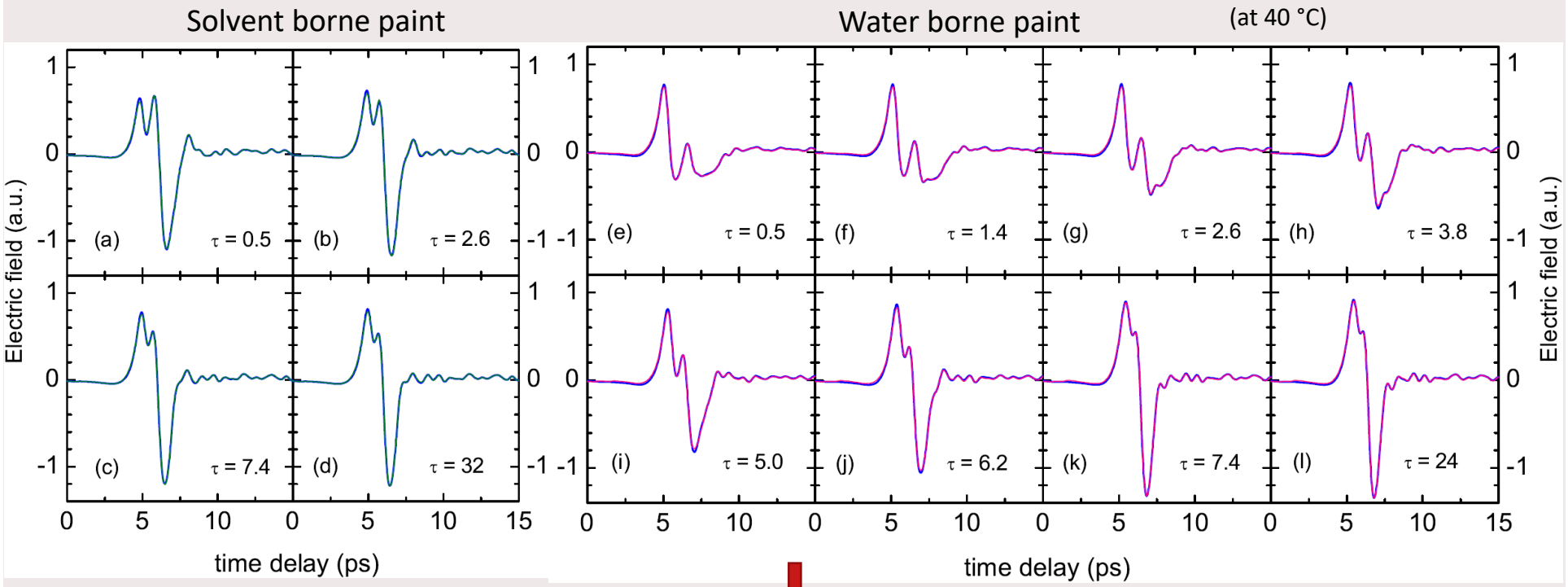
THz radiation probing drying coatings . . . universally for all automotive coatings



$d, \epsilon(\omega)$

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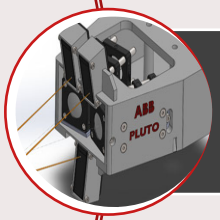
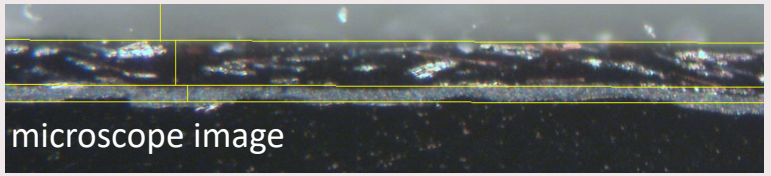
Validation test procedure and benchmark techniques

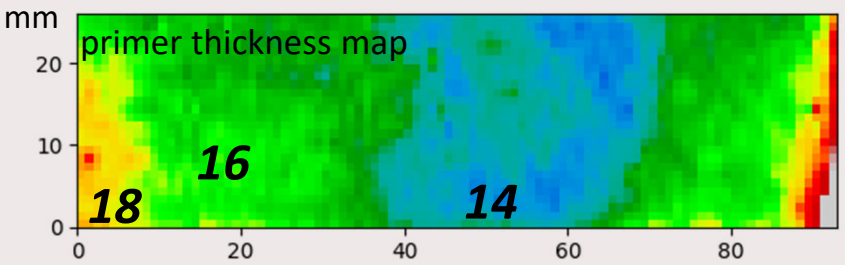
Microscope thickness
- Cutting paint sample (laser or mechanical)
- Embedding in epoxy
- Drying epoxy and polishing surface

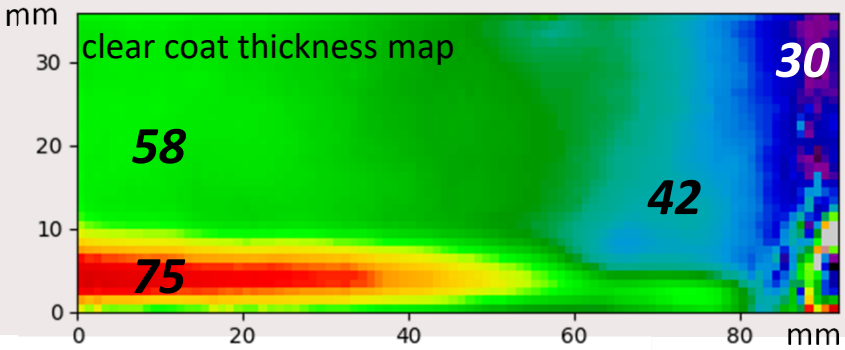


THz thickness
- measurements with paint analyzer
- using predetermined optical properties

Benchmark thickness
- Fischer, Elcometer, Defelsko







Optics Express 29, 7518 (2021)

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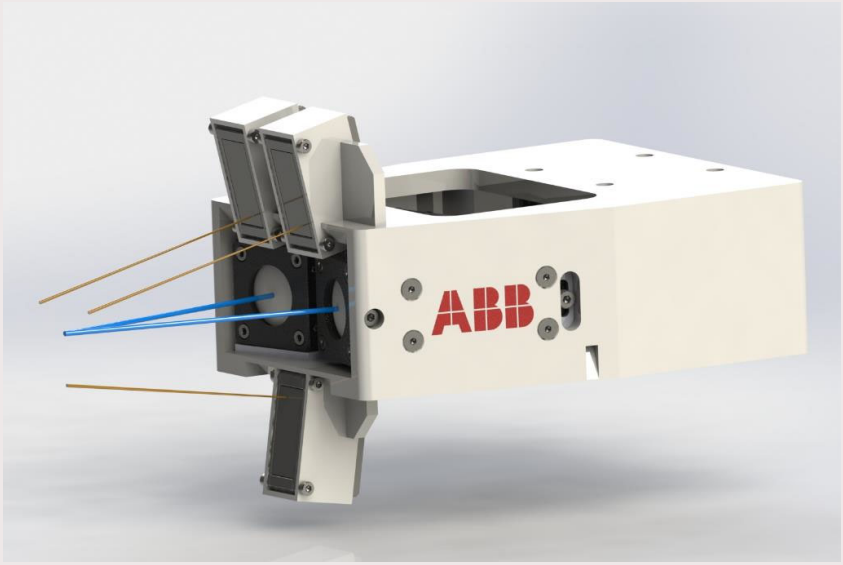
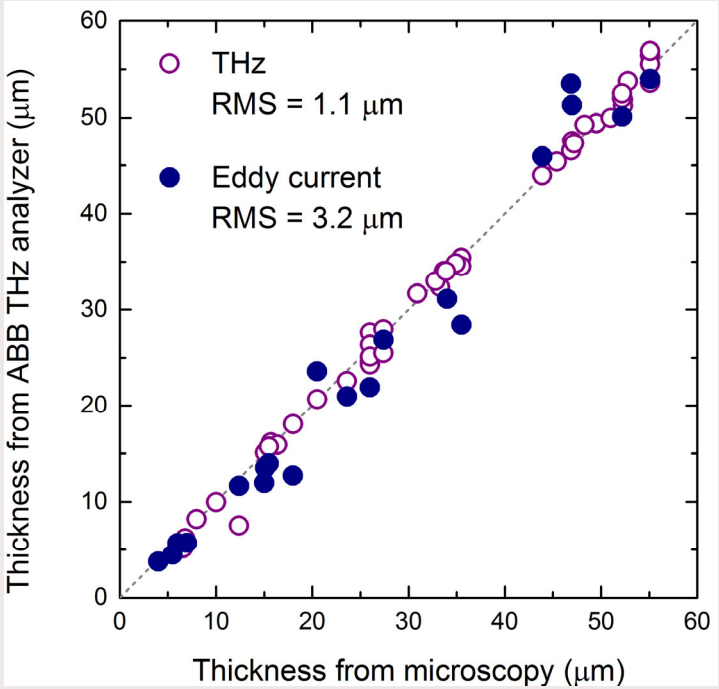
Overall performance of a THz paint analyzer





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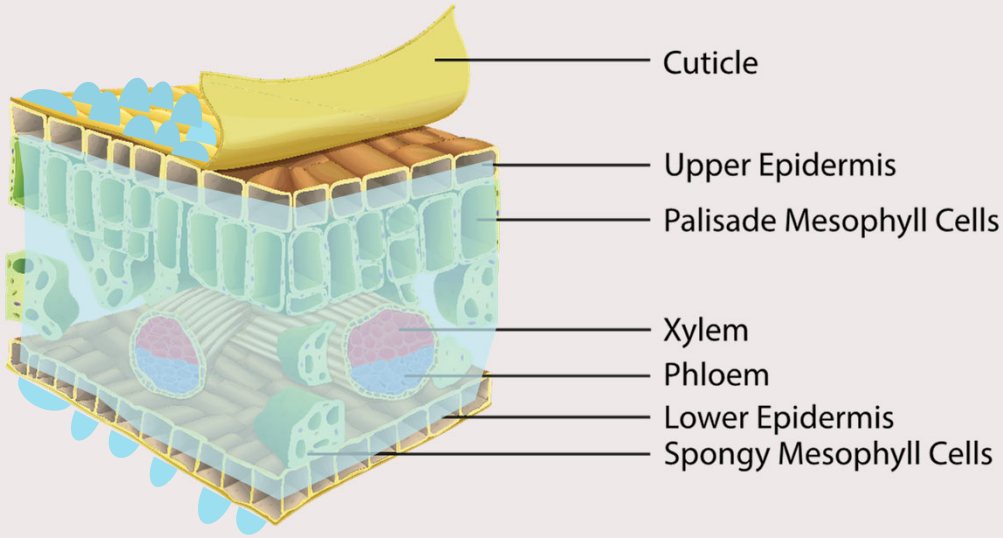
Outlook

Determination of leaf wetness for plant illness prediction



Hybrid analysis: physical models reinforcing data-based signal processing

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Summary

The road to THz applications with societal relevance

- Novel application with an innovative use
- Have domain know-how
- Deal with inherent obstacles
  (like costs, form factor, etc.)
- For sensing: signal processing makes the difference

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