

WMC-6

Active FMCW Radar Imaging for Long-Range Wireless Passive Sensors

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Laboratoire conventionné
avec l'Université Fédérale
de Toulouse Midi-Pyrénées

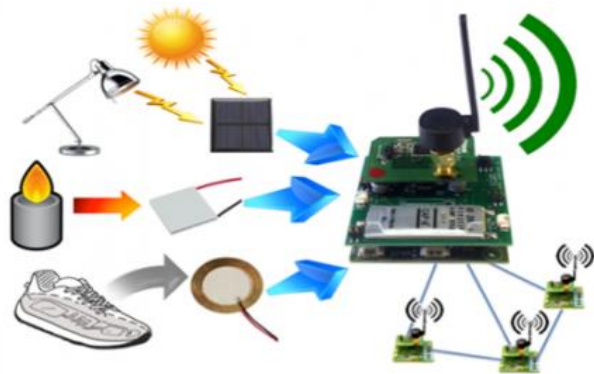


- **Context – RFID sensor technology**
- **Overview on batteryless and wireless EM Sensors**
- **Remote reading of passive EM sensors**

Context – RFID sensor technology

Context

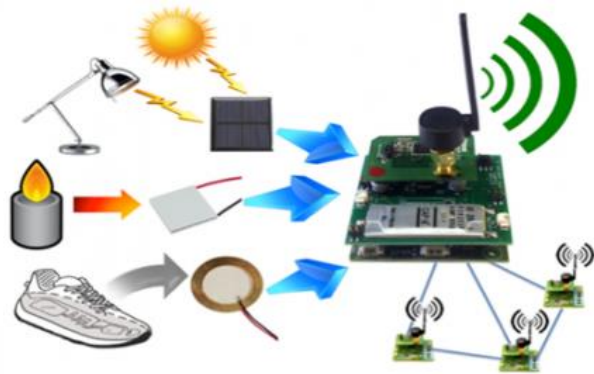
- **Internet of Things (IoT)** : internet connected nodes with IP addresses
- **Nodes with sensing, identification and communication capabilities**



➔ **wireless sensors** are a part of IoT
(WSN)

Context

- **Internet of Things (IoT)** : internet connected nodes with IP addresses
- **Nodes with sensing, identification and communication capabilities**



➔ **wireless sensors** are a part of IoT (WSN)

- **Example : RFID sensors (Radio Frequency Identification)**
 - RFID tag + sensing device
 - Based on the existing wireless protocols for RFID technologies
 - Typical chip design of RFID sensor ICs includes : RF front-end, digital processor, memory, bus interface and power supply management unit

Focus on RFID Sensor Technologies

ACTIVE

Internal battery

Communication range : > 100 meters

Continuous monitoring and recording sensor data

Cost in 2017 : 5 \$ - 20 \$

Focus on RFID Sensor Technologies

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BAP

Internal power source to power on + energy transferred from the RF reader

Communication range : up to 100 meters

Read & transfer sensor data only when receives signal from reader

Cost in 2017 : 1 \$ - 5 \$

Focus on RFID Sensor Technologies

ACTIVE

Internal battery

Communication range : > 100 meters

Continuous monitoring and recording sensor data

Cost in 2017 : 5 \$ - 20 \$

BAP

Internal power source to power on + energy transferred from the RF reader

Communication range : up to 100 meters

Read & transfer sensor data only when receives signal from reader

Cost in 2017 : 1 \$ - 5 \$

PASSIVE

BATTERYLESS

Communication range : <10 meters

Read & transfer sensor data only when tag is powered by reader

Cost in 2017 : < 1 \$

Brief Overview on Batteryless and Wireless EM Sensors

Sensing devices based on EM transduction

■ Principle

change $\Delta\Phi$ of the physical (or chemical) quantity



variation Δv of an electromagnetic descriptor

Sensing devices based on EM transduction

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variation Δv of an electromagnetic descriptor

■ **Passive** (batteryless) + **wireless** + **no electronics** (no IC, “chipless”)

- ✓ Unlimited energy autonomy
- ✓ Long-term measurement stability
- ✓ Low-cost of fabrication
- ✓ Small size and weight
- ✓ Operability in harsh or severe environments

From sensing devices to sensors

Challenges

- ✓ High reading range (up to 100 m)
- ✓ High measurement sensitivity
- ✓ High linearity
- ✓ Large full-scale (or dynamic/total) range

Key sensor descriptors

$$\Delta v / \Delta \Phi$$

$$R^2$$

$$\max[\Phi] - \min[\Phi]$$

From sensing devices to sensors

Challenges

Key sensor descriptors

- ✓ High reading range (up to 100 m)
- ✓ High measurement sensitivity
- ✓ High linearity
- ✓ Large full-scale (or dynamic/total) range
- ✓ High measurement resolution*
(target : < 1%)

$$\Delta v / \Delta \Phi$$

$$R^2$$

$$\max[\Phi] - \min[\Phi]$$

$$\min[\Delta \Phi] / (\max[\Phi] - \min[\Phi])$$

* smallest detectable incremental change of the physical quantity $\Delta \Phi$ that can be detected in the EM descriptor Δv

From sensing devices to sensors

Challenges

Key sensor descriptors

- ✓ High reading range (up to 100 m)
- ✓ High measurement sensitivity
- ✓ High linearity
- ✓ Large full-scale (or dynamic/total) range
- ✓ High measurement resolution*
(target : < 1%)
- ✓ High measurement precision**

$$\Delta v / \Delta \Phi$$

$$R^2$$

$$\max[\Phi] - \min[\Phi]$$

$$\min[\Delta \Phi] / (\max[\Phi] - \min[\Phi])$$

$$\sigma$$

* smallest detectable incremental change of the physical quantity $\Delta \Phi$ that can be detected in the EM descriptor Δv

** measure of the statistical variability of the EM descriptor measuring exactly the same value of Φ a number of times

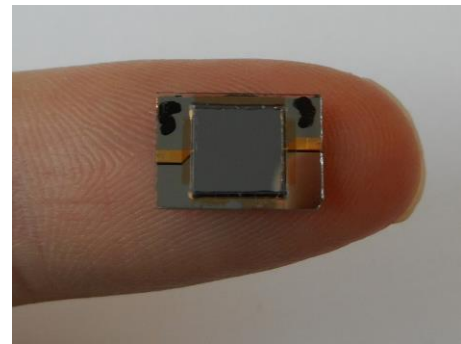
Targeted applications

- Structure Health Monitoring (**SHM**) of infrastructures in, e.g., Nuclear, Satellites & Aeronautics domains
- Indoor & outdoor operability in **severe and harsh environment**
($T > 500^{\circ}\text{C}$, $T < -50^{\circ}\text{C}$, nuclear radiations, ...)

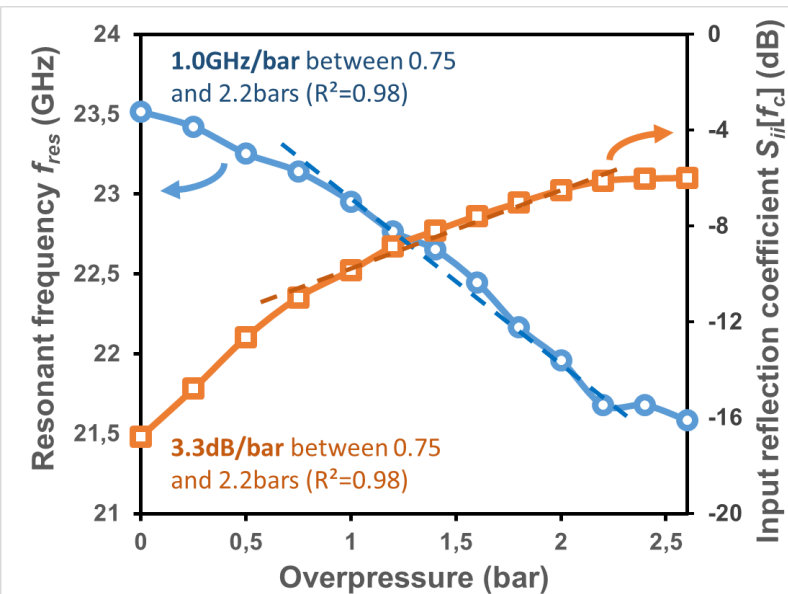
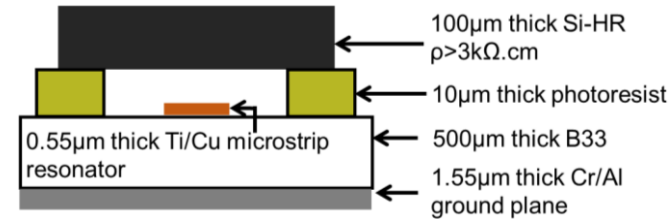
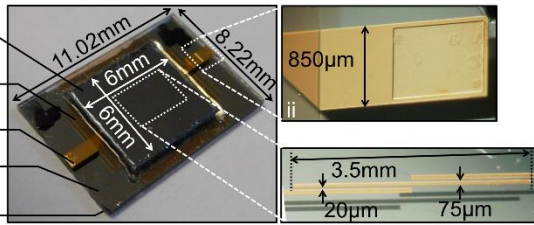
Very first passive EM sensing devices

- 2002 :** **First Moisture Sensor :** *R Yogi et al. Meas. Sci. Tech. 2002*
Permittivity variation of paper substrate from planar resonator
- 2004 :** **First Gas Sensor :** *Mc. Grath et al., Proc. SPIE, 2004*
Permittivity variation of a planar resonator coated with CNT
- 2005 :** **First Strain Sensor :** *Chuang et al., Rev. Scient. Inst., 2005*
Length variation of a microwave cylindrical cavity due to a strain
- 2007 :** **First Pressure Sensor :** *Jatlaoui et al., EuMC, Germany, 2007*
Deflection of a thin membrane coupled to a planar mm-wave resonator via evanescent modes
- 2009 :** **First Fatigue Crack Sensor :** *R Matsuzaki et al., Smart Mat. Str*
Modification of the electrical length of a patch antenna
- 2010 :** **First Airflow Sensor :** *Y. Zhao et al., Sensors and Act. 2010*
Deflection of a thin membrane coupled to a cavity via evanescent modes

Passive pressure EM sensing device*



100 μ m thick Si-HR
 $\rho > 3k\Omega \cdot \text{cm}$
 10 μ m thick photoresist
 0.55 μ m thick Ti/Cu
 500 μ m thick B33
 1.55 μ m thick Cr/Al ground plane



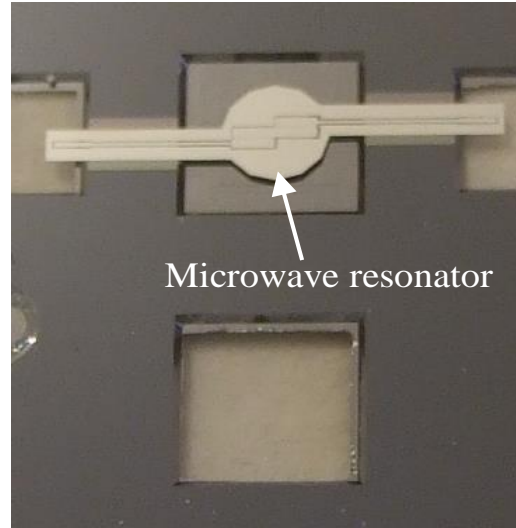
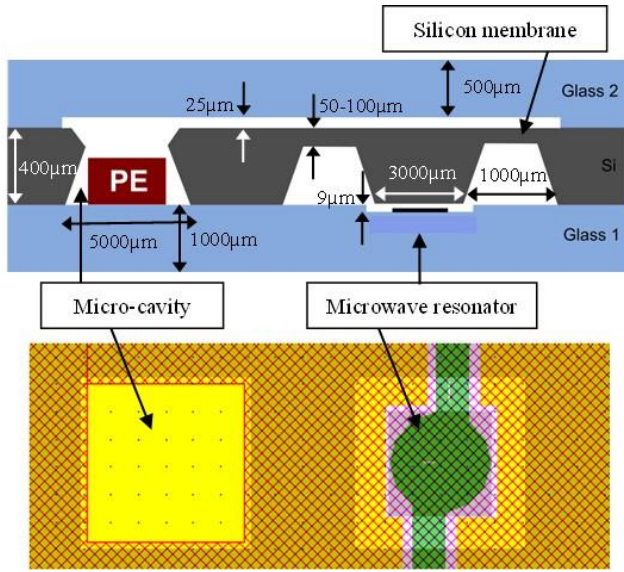
Measured Sensitivity of **1.0GHz/bar**
 and **3.3dB/bar** between **0.75 to 2.2 bars**

Dynamics of **4.9dB** between **0.75 to 2.2bars**
 ⇒ Interesting for radar measurement (radar
 frequency band of [22.8 – 24.8 GHz]

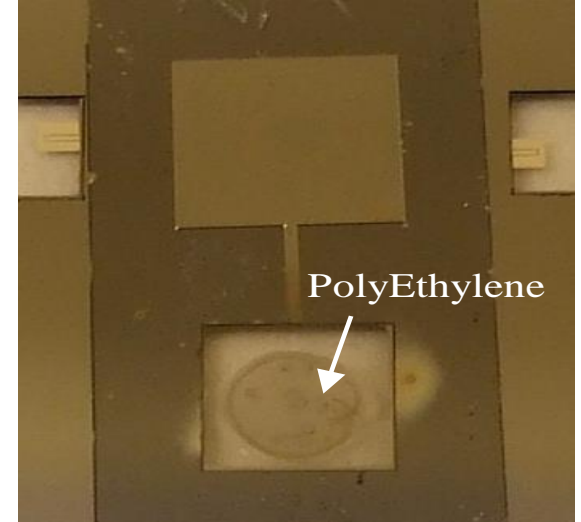
*J. PHILIPPE et al., IMS 2018, Philadelphia, United States of America, 10-15 Jun 2018

*J. PHILIPPE et al., EUROSENSORS 2017, Paris, France, 3-6 Sept 2017

Nuclear radiation passive EM sensing device*



Top side



Bottom side

Resonant Frequency Shift reaches 8% after e-beam irradiation (20kGy)

Supported by :



* E. DEBOURG *et al.*, *IEEE Sensors*, Orlando, Florida, USA, 30 Oct. – 2 Nov. 2016

* C. ARENAS *et al.*, *European Microwave Conf.* 2017

Remote reading of Passive EM Sensors

Different Remote Measurement techniques

Ref.	Device	Parameter measured	Interrogation Frequency	Wireless interrogation	Interrogation distance
[1]	EM bandgap and NTC thermistor	Temperature	2 – 2.6 GHz	PNA	10 cm
[2]	μm-wave circuit	Pressure	10.6 GHz	PNA	10 cm
[3]	μm-wave circuit	Humidity	6 – 7 GHz	VNA	30 cm
[4]	mm-wave identification sensor	Pressure	57.8 GHz	PNA	62 cm
[5]	WG mode resonator	Gas concentration	28.8 – 31 GHz	FMCW Radar	3.4 m
[6]	SAW	Temperature	433 MHz	Radar-like reader	10 m
[7]	Van-Atta reflectarray	Humidity	22.8 – 24.8 GHz	FMCW Radar	58 m

[1] S. PRERADOVIC *et al.*, IEEE Sensors Conference, 1-4 Nov. 2010, Kona, HI, USA
 [2] A. IBRAHIM *et al.*, Sensors and Actuators A: Physical, Vol. 165, Issue 2, February 2011, pp. 200-206
 [3] E. M. AMIN *et al.*, IEEE International Conference on RFID-Technologies and Applications, 5-7 Nov. 2012, Nice, France
 [4] D. HOTTE *et al.*, IEEE Sensor Journal, vol. 16, no. 14, pp. 5583-5587, July15, 2016
 [5] H. HALLIL *et al.*, IEEE Sensors Conference, 1-4 Nov. 2010, Kona, HI, USA
 [6] P. VARSHNEY *et al.*, IEEE International Frequency Control Symposium, 21-24 May 2012, Baltimore, MD, USA
 [7] D. HENRY *et al.*, IEEE Transactions on Microwave Theory and Techniques, Vol. 65, No. 12, pp. 5345-5354

Proposed solution for remote reading

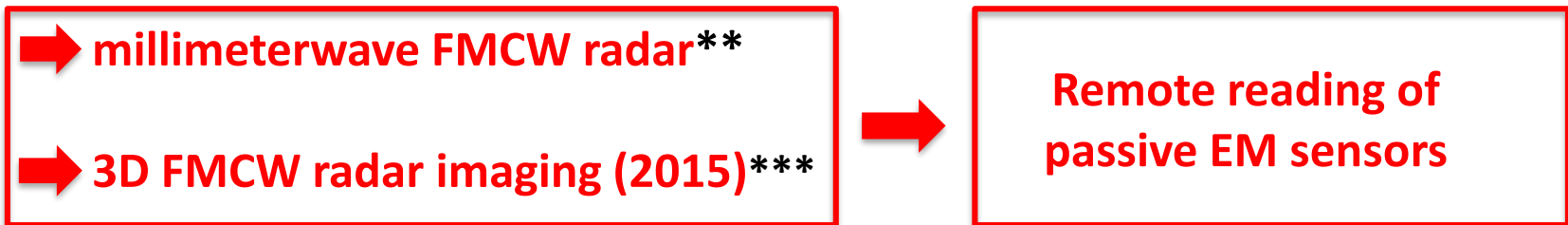
- **Measurement of sensors EM echo variability* (2008 →)**
Conversion of a physical (or chemical) quantity fluctuation $\Delta\Phi$ into the variation of the sensor EM echo $\Delta\sigma$
- **Use of FMCW radar technology (2010 →)**

* M. JATLAOUI *et al.*, *Asia Pacific Microwave Conference*, Hong Kong and Macao, China, 2008

Proposed solution for remote reading

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More specifically:



* M. JATLAOUI *et al.*, *Asia Pacific Microwave Conference*, Hong Kong and Macao, China, 2008

** Patent WO 2010/136388

*** D. HENRY *et al.*, *IEEE International Microwave Symposium*, 17-22 May 2015, Phoenix, USA

The choice of millimeter-wave regime

- Use **high-frequency** carrier (such as, 24GHz, 60GHz, 77GHz, 122GHz,...) for the wireless interrogation of EM sensors rather than low frequency offers:

The choice of millimeter-wave regime

- Use **high-frequency** carrier (such as, 24GHz, 60GHz, 77GHz, 122GHz,...) for the wireless interrogation of EM sensors rather than low frequency offers:
 - ✓ **Higher** electrical length **separation** distance to objects located around the sensor (more insensitive to impedance mismatch due to the proximity of metals)
 - ✓ Higher robustness to **multi-paths**
 - ✓ **Smaller** sensor and radar antenna **sizes**
 - ✓ **Higher** frequency **bandwidth** (useful for sensors ident. and depth resolution)
 - ✓ **Compact design** for beamforming, multi-beam or beam-steering Radar for simultaneously interrogating multiple passive EM sensors

Wireless FMCW Radar Interrogation Technique

- **Proposed solution**
 - ✓ Performing the beam scanning of the radar main lobe* and/or translating the radar** for illuminating the scene at different angles and obtaining a **3D radar image** (Active Radar Imaging technique)
 - ✓ Compute statistical **estimator ϵ** of the physical quantity **Φ** from the appropriate **combination of beat frequency spectra** measured in many directions around the sensor direction

Best option than measurement with only one beat frequency spectrum* (no impact on measurement of misalignment between Tx-antenna and the sensor)**

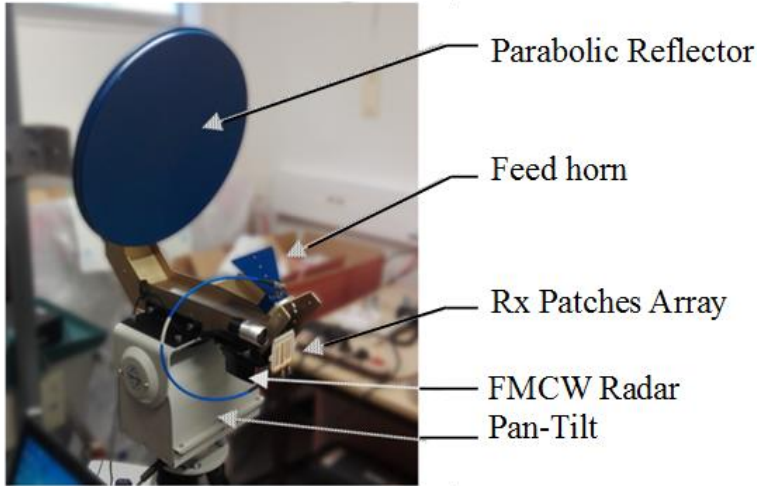
*D.HENRY *et al.*, *IEEE International Microwave Symposium*, 17-22 May 2015, Phoenix, USA

**D. HENRY *et al.* *IEEE International Microwave Symposium*, 4-9 June 2017, Honolulu, Hawaii

***F. CHEBILA *et al.*, *IEEE AP-S.*, Toronto, Ontario, Canada, 2010

24GHz FMCW Radar with Mechanical Beam Scanning

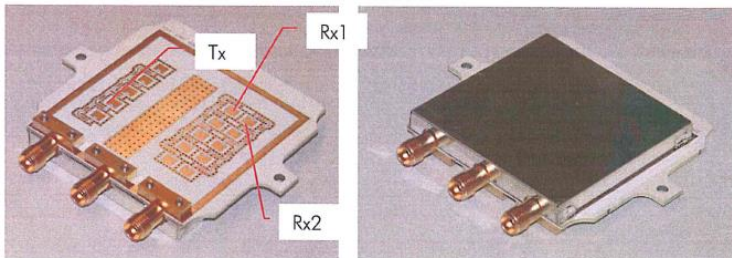
Tx-Antenna



FMCW Radar Characteristics*

Carrier Frequency	23.8 GHz
Modulation bandwidth	2 GHz/250 MHz
Ramp Duration	1 ms
Number of samples	1024
Output Power	20 dBm (100 mW)

Rx-Antenna (Rx1 and Rx2)



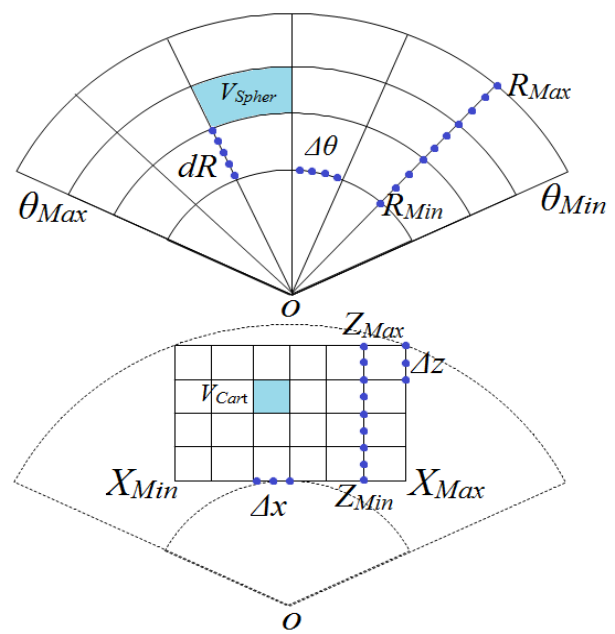
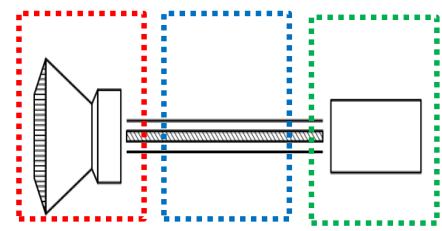
3-dB antenna characteristics and antenna gain :

- Rx1 : 60 deg Azimuth, 25 deg Elevation 10dBi gain
- Rx2 : 70 deg Azimuth, 25 deg Elevation 9dBi gain
- Tx : 2 deg Azimuth, 2 deg Elevation 33dBi gain

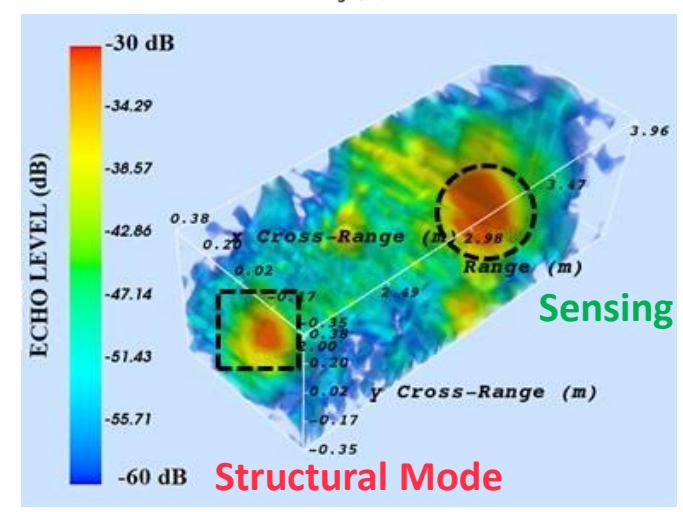
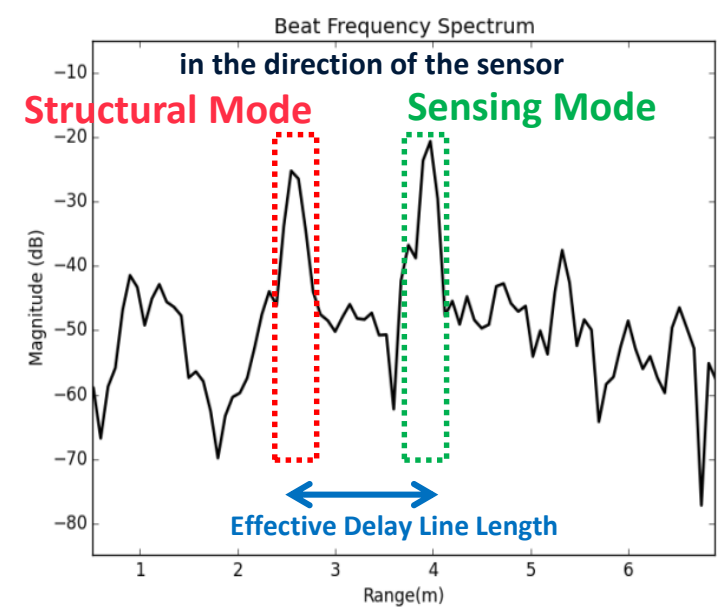
*From IMST GmbH

Radar imaging technique for passive EM sensors

Example of passive EM sensor

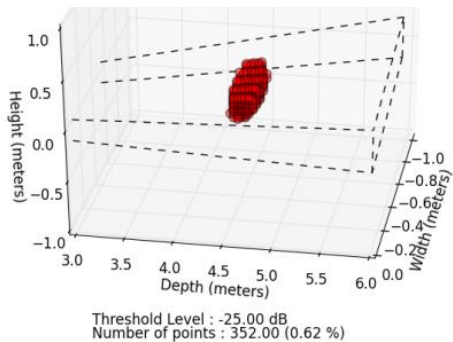


Beam scanning

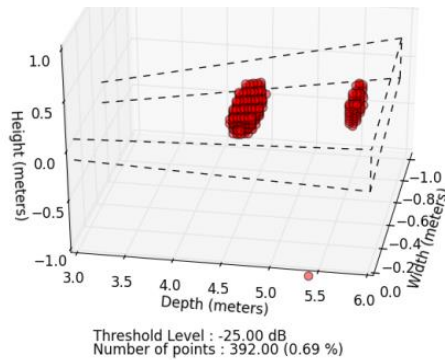


Remote derivation of sensing device impedance*

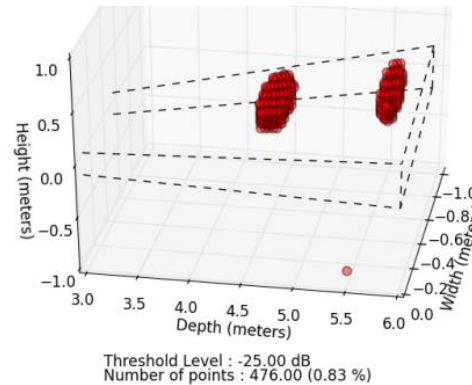
Z=50 Ω
0 cell



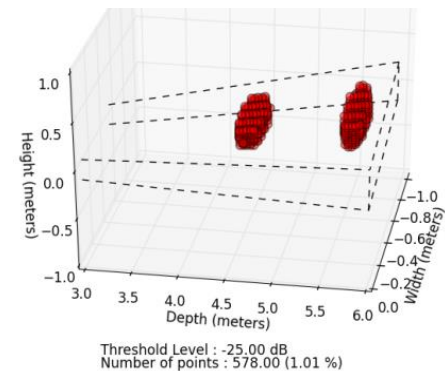
Z=30 Ω
40 cells



Z=17 Ω
124 cells



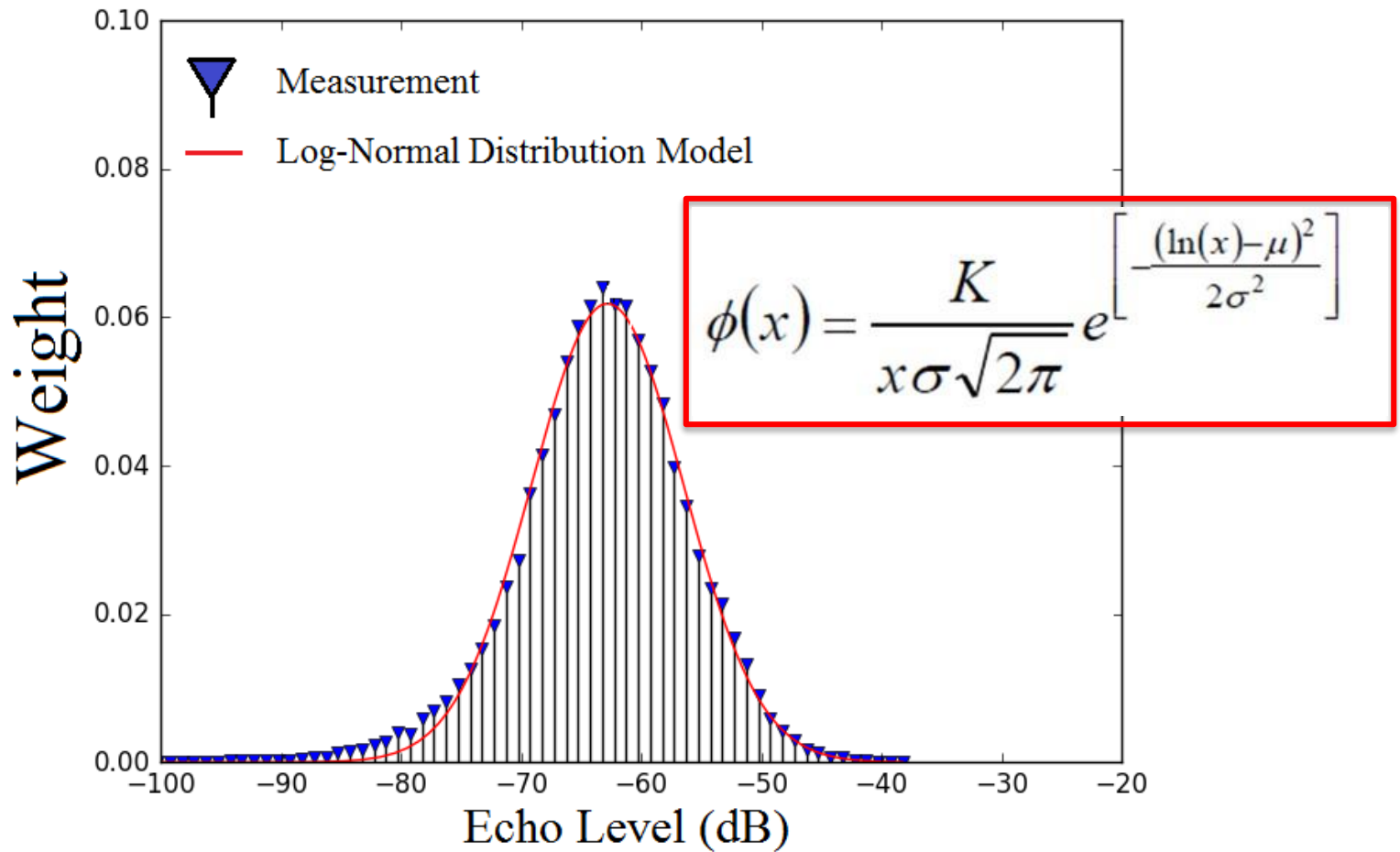
Z=0 Ω
246 cells



*D.HENRY et al., *IEEE International Microwave Symposium*, 17-22 May 2015, Phoenix, USA

Remote derivation of sensing device impedance*

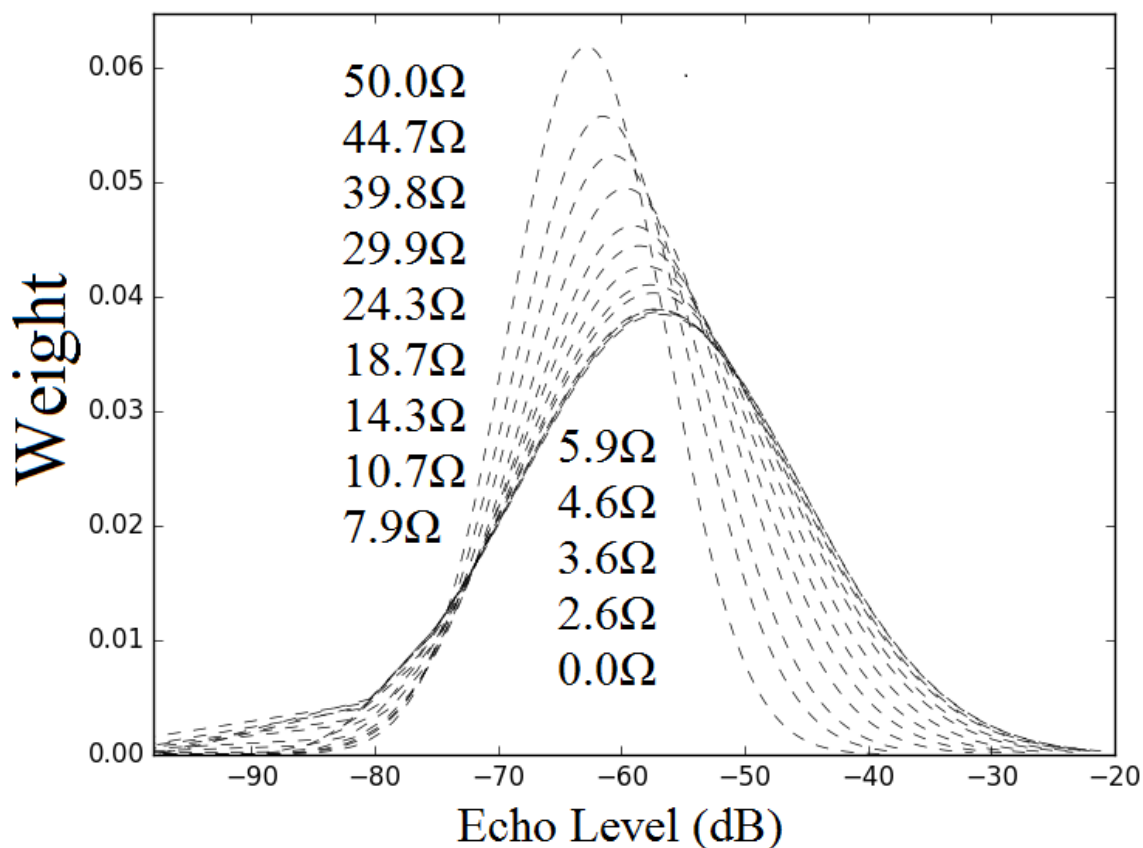
Distribution of echo level around the sensing device



*D.HENRY *et al.*, EuMC 2016, London, UK, 4-6 Oct 2016

Remote derivation of sensing device impedance*

Distribution of echo level around the sensing device



*D.HENRY *et al.*, EuMC 2016, London, UK, 4-6 Oct 2016

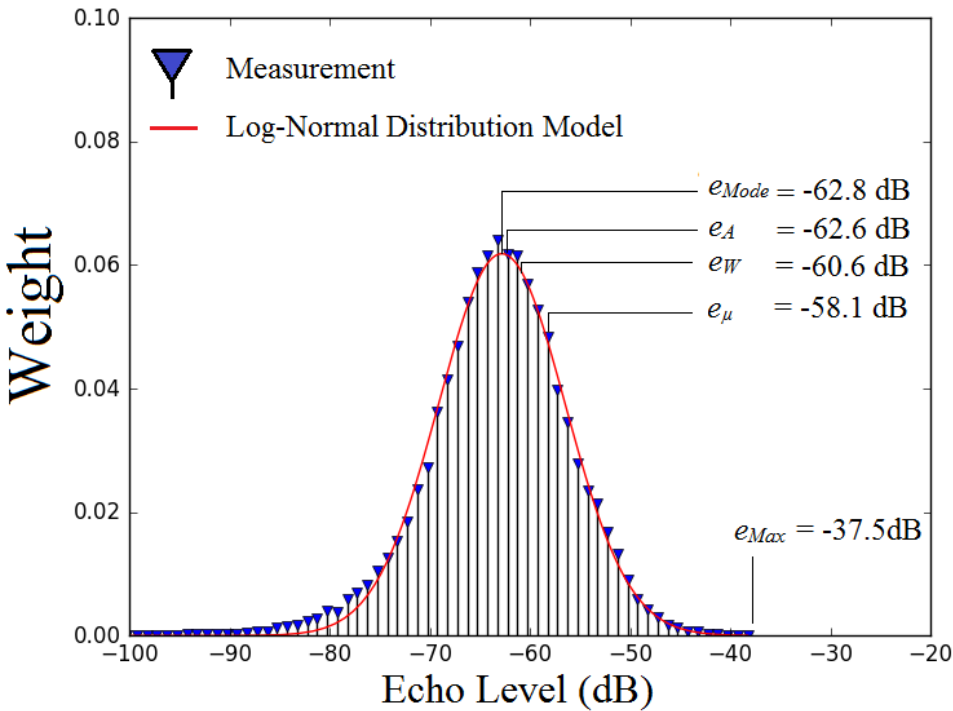
Remote derivation of sensing device impedance*

N : Total number of cells in the volume under consideration

$\{P_k, 1 \leq k \leq N\}$: Set of echo levels in the volume under consideration

M such as : $P_{M-1} = e_{Max}$

Proposed statistical estimators



Maximum: $e_{Max} = \text{Max}\{P_k, 1 \leq k \leq N\}$

Arithmetic mean: $e_A = \sum_{n=0}^{M-1} \frac{P_n}{N}$

Weighted mean: $e_W = \sum_{n=0}^{M-1} P_n \cdot W_n$

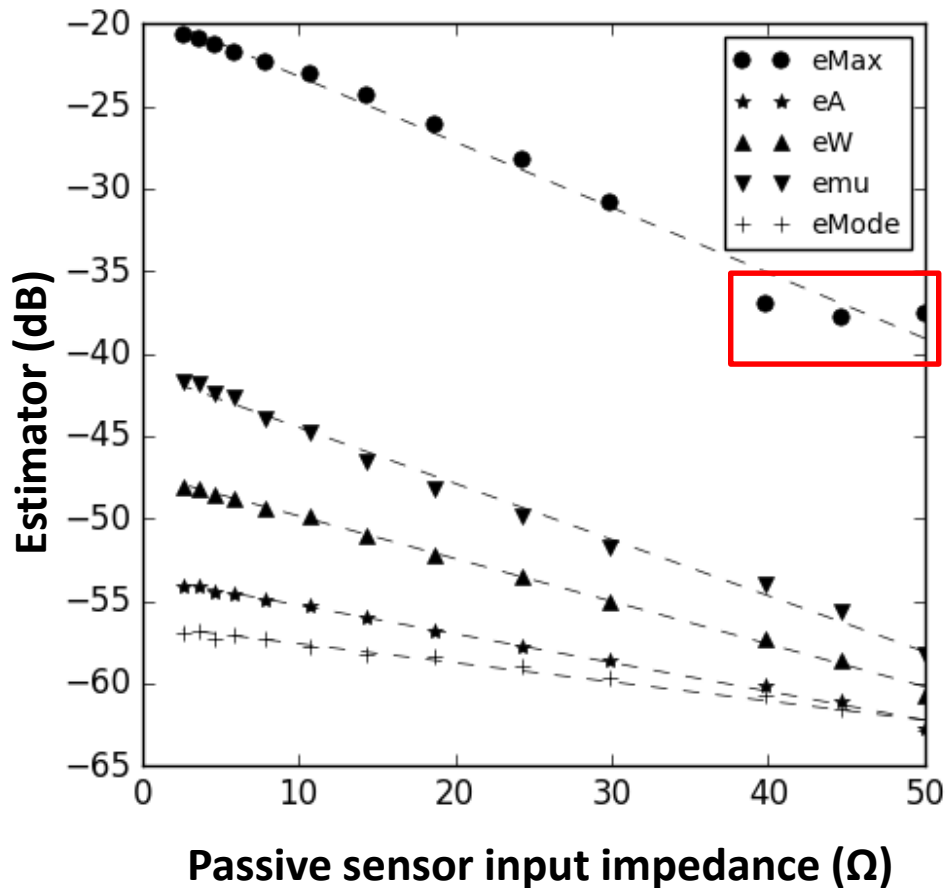
Mode: $e_{mode} = \exp(\mu - \sigma^2)$

Shift: $e_\mu = \exp(\mu)$

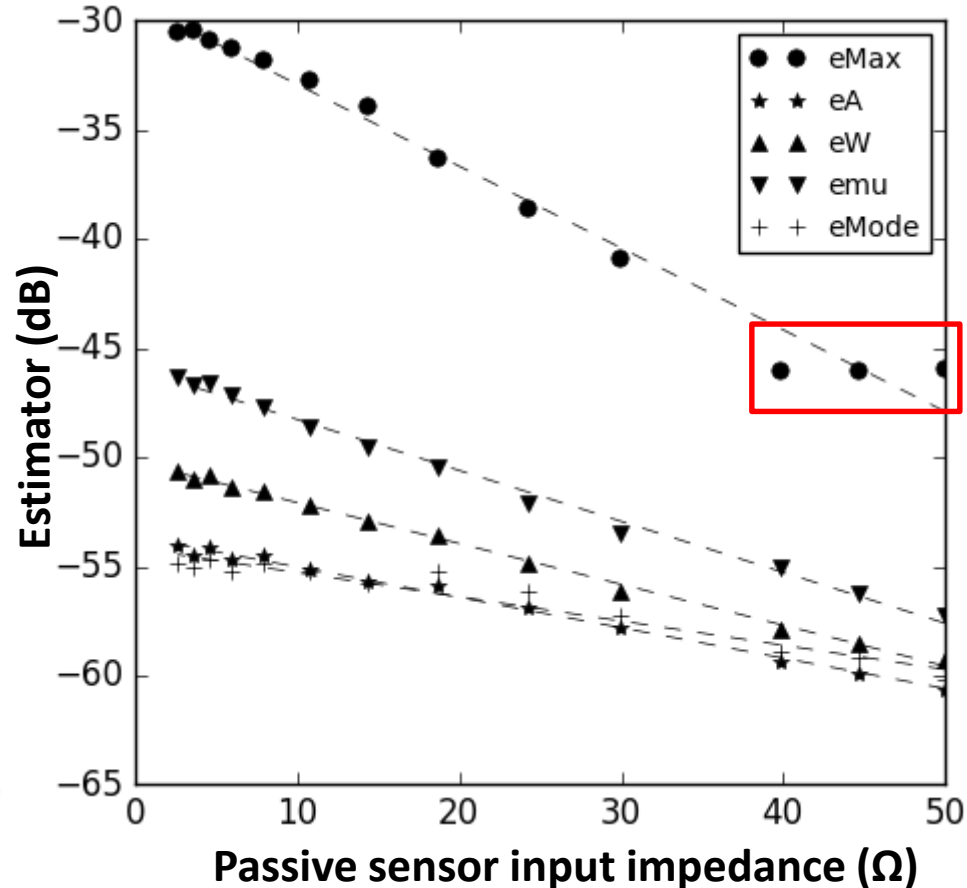
*D.HENRY *et al.*, EuMC 2016, London, UK, 4-6 Oct 2016

Remote derivation of sensing device impedance*

at 2 meters from the radar



at 5.5 meters from the radar

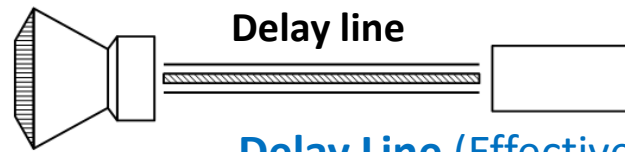


*D.HENRY *et al.*, EuMC 2016, London, UK, 4-6 Oct 2016

Application to temperature EM sensing device*

Antenna

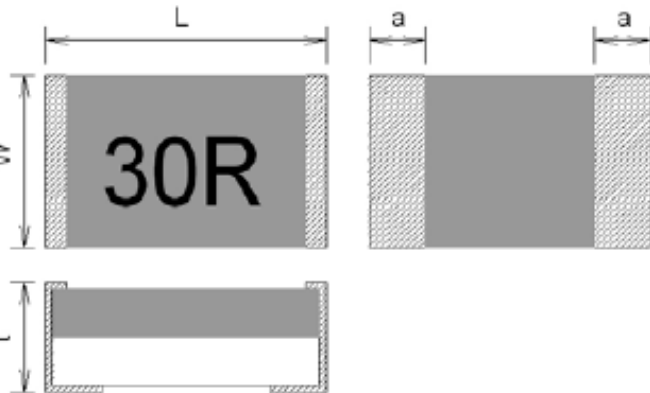
Thermistor



Delay line

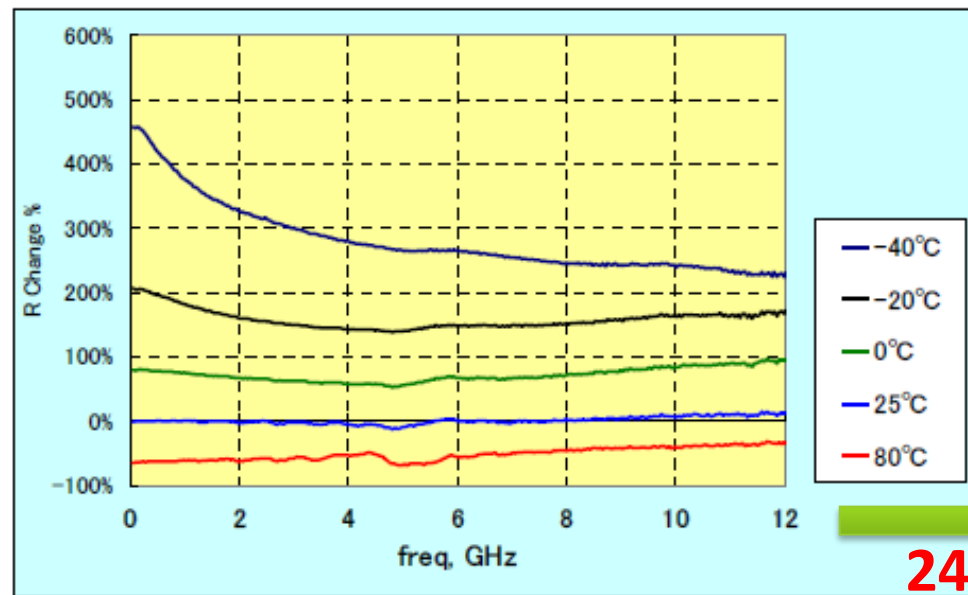
Delay Line (Effective Length : 1.35 m)

<Dimension>



	Dimension (mm)
L	2.0 ± 0.2
W	1.25 ± 0.2
a	0.4 ± 0.2
t	0.9MAX

<Frequency vs. Temp characteristic>



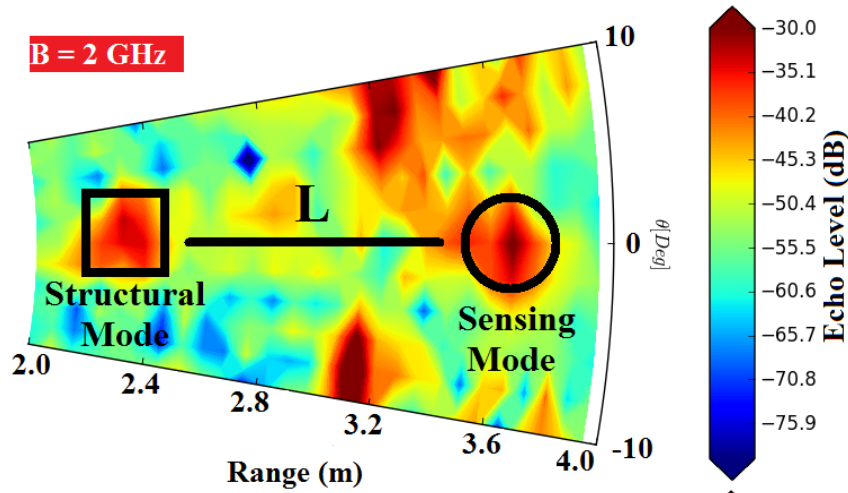
24 GHz

SSM Thin Film Technology – SMT High Frequency Chip Thermistor 0805

*D.HENRY et al., IEEE International Microwave Symposium, 22-27 May 2016, San Francisco, CA, USA

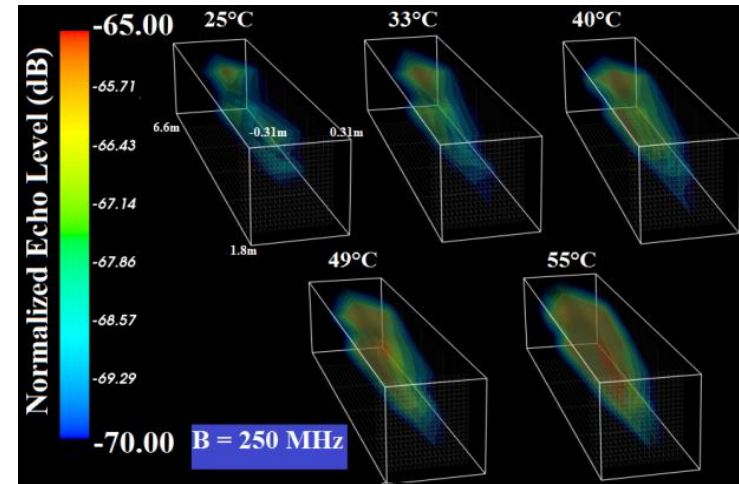
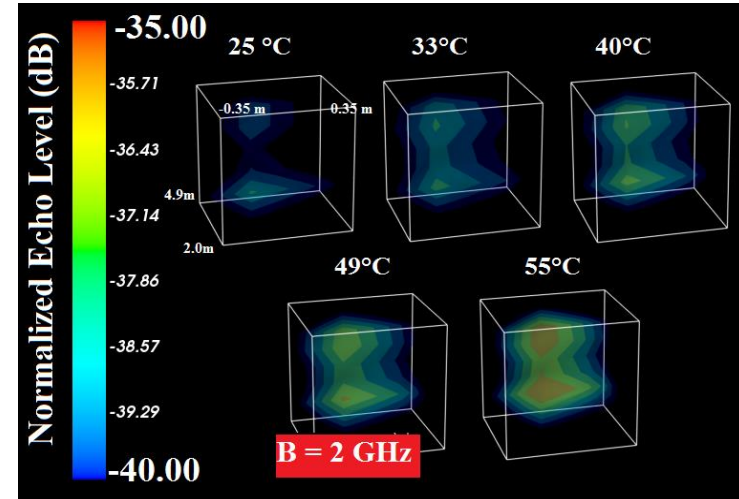
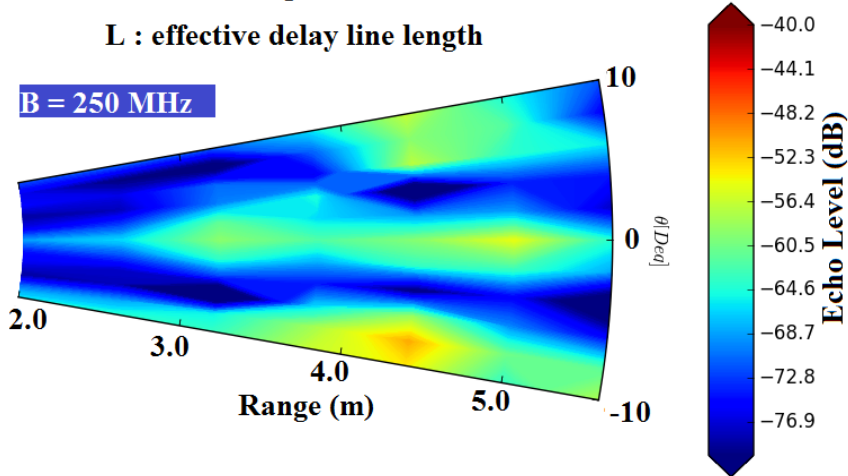
Application to temperature EM sensing device*

Theoretical depth resolution : 7.5 cm



L : effective delay line length

Theoretical depth resolution : 60 cm

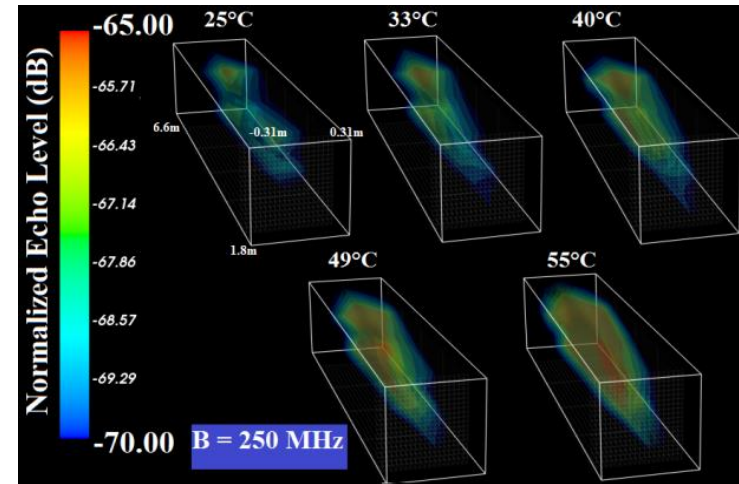
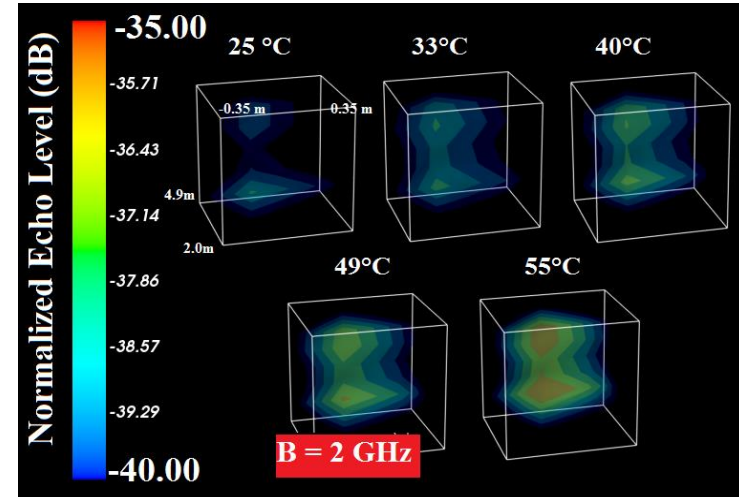


*D.HENRY *et al.*, *IEEE Int.Microwave Symposium*, 22-27 May 2016, San Francisco, CA, USA

Application to temperature EM sensing device*

Measured **RF thermistor** dynamic range of 5dB only

But dynamic range of 15 dB is available (but not exploited) at 2-2.5 meters.



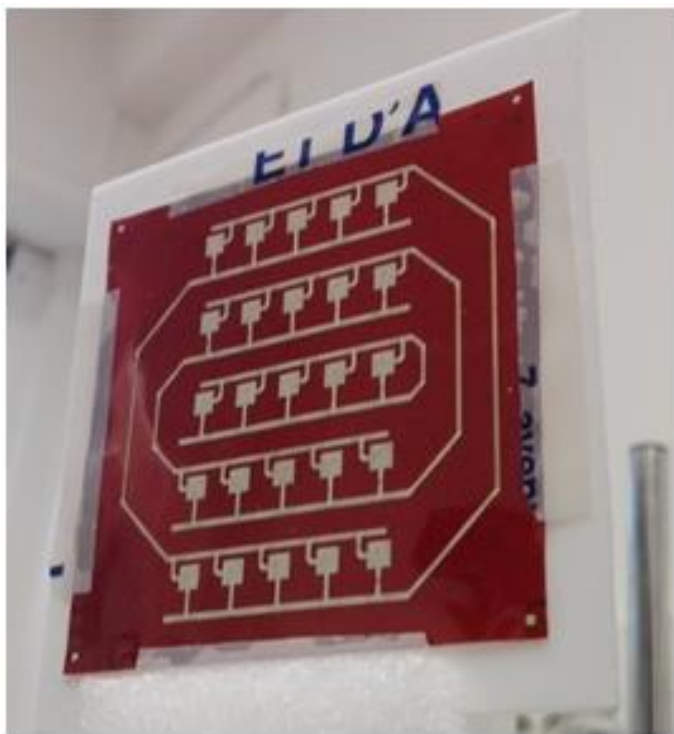
*D.HENRY et al., IEEE Int.Microwave Symposium, 22-27 May 2016, San Francisco, CA, USA

Application to humidity sensor device*

In collaboration with:



Retrodirective and depolarizing humidity sensors**



Key Parameters

- ✓ Dimensions : 74x74 mm²
- ✓ Inkjet printed technology
- ✓ Five side-by-side linear antenna arrays
- ✓ Flexible substrate (Kapton: permittivity very sensitive to humidity)
- ✓ Ground plane (tag not detunes by proximity of metals)

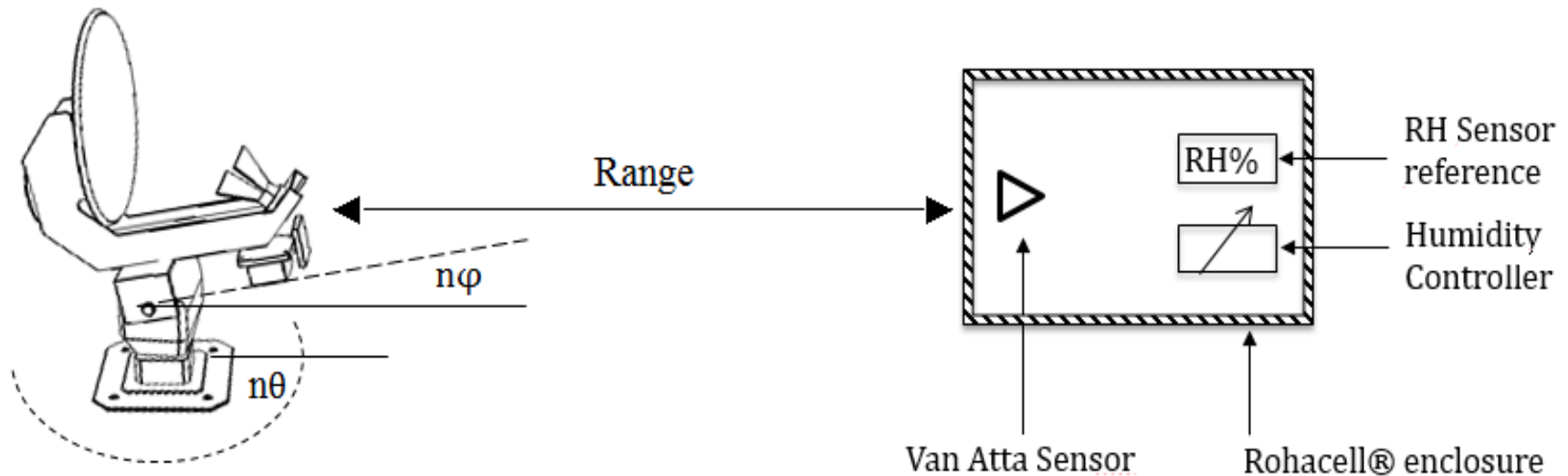
* D. HENRY et al. *IEEE International Microwave Symposium*, 4-9 June 2017, Honolulu, Hawaii

** J. G. D. HESTER et al. *IEEE International Microwave Symposium*, 22-27 May 2016, San Francisco, CA, USA

Application to humidity sensor device*

Active FMCW radar Imaging technique

Derivation of the variation of RH from the remote measurement of echo level variation at the location of the sensing device



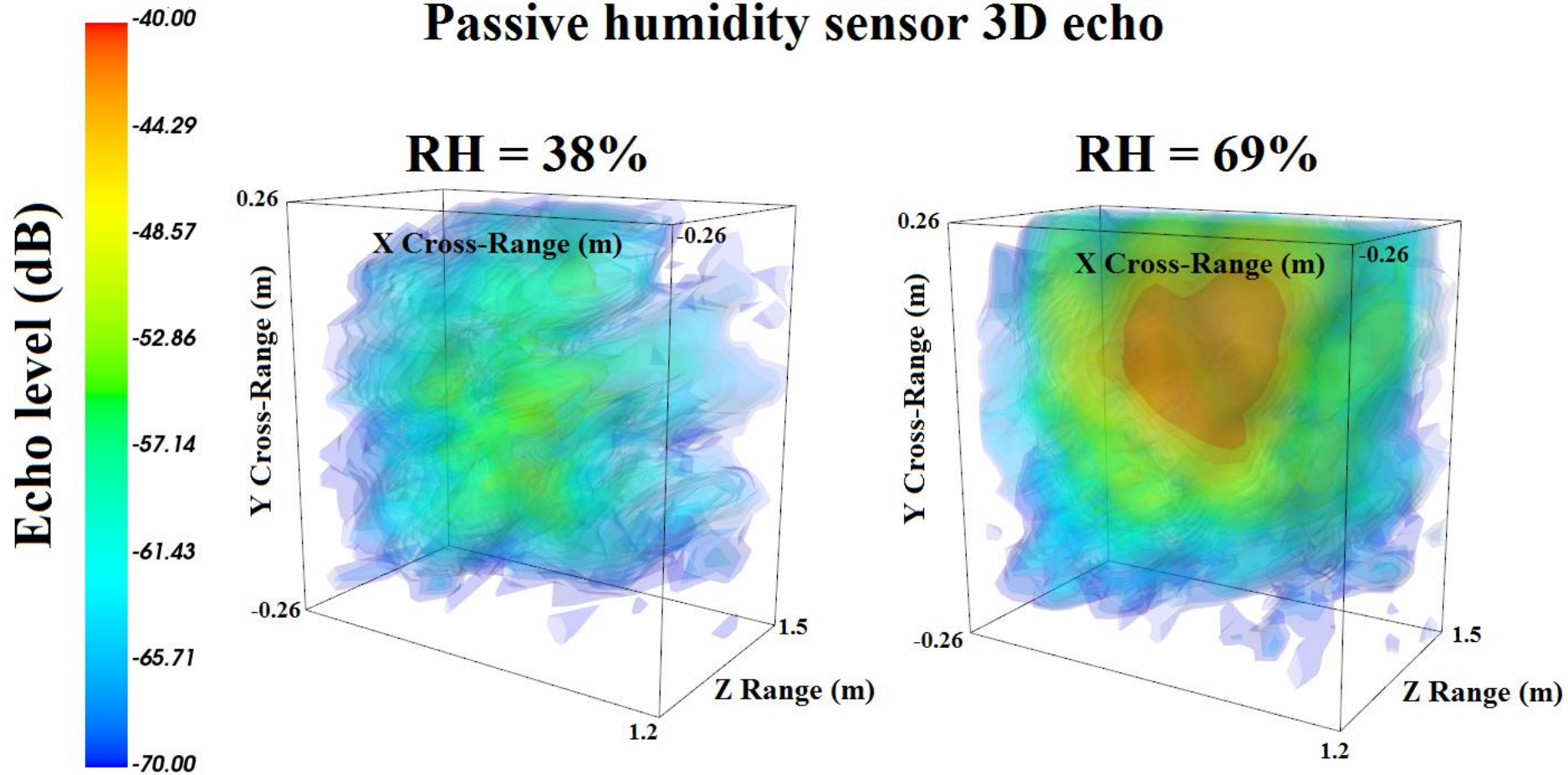
Recording of $n_\theta \cdot n_\phi$ beat frequency spectra

➔ 3D Image from echo level in the volume under consideration

* D. HENRY *et al.* IEEE International Microwave Symposium, 4-9 June 2017, Honolulu, Hawaii

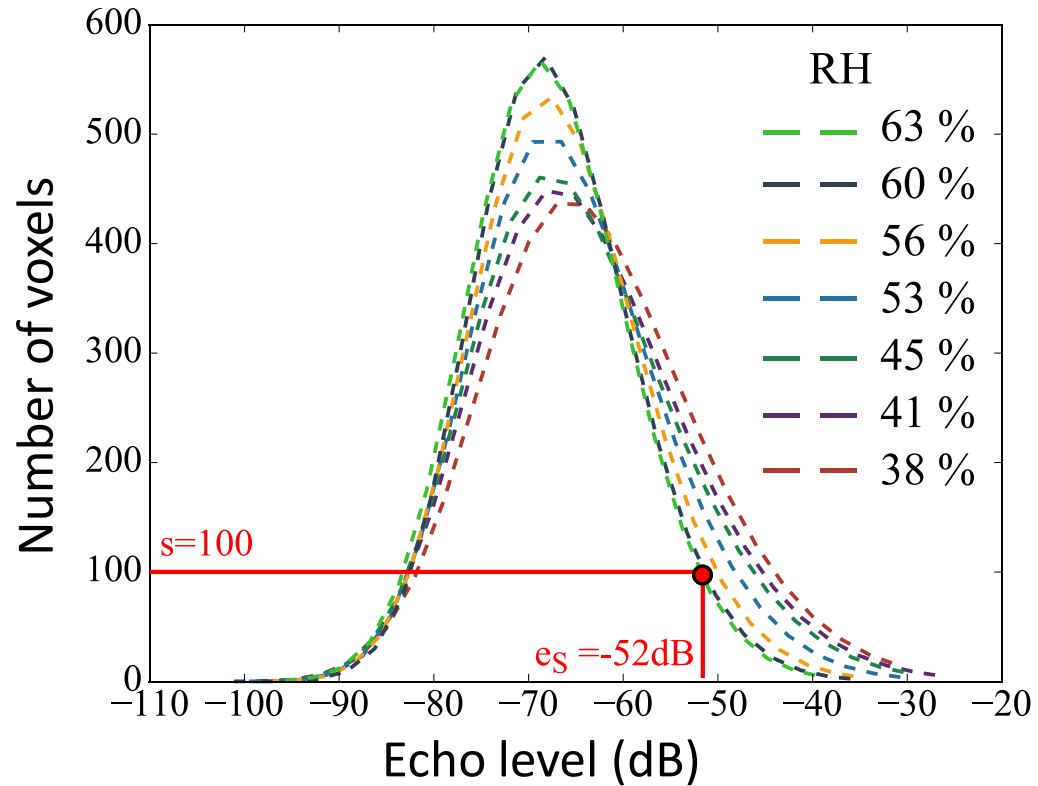
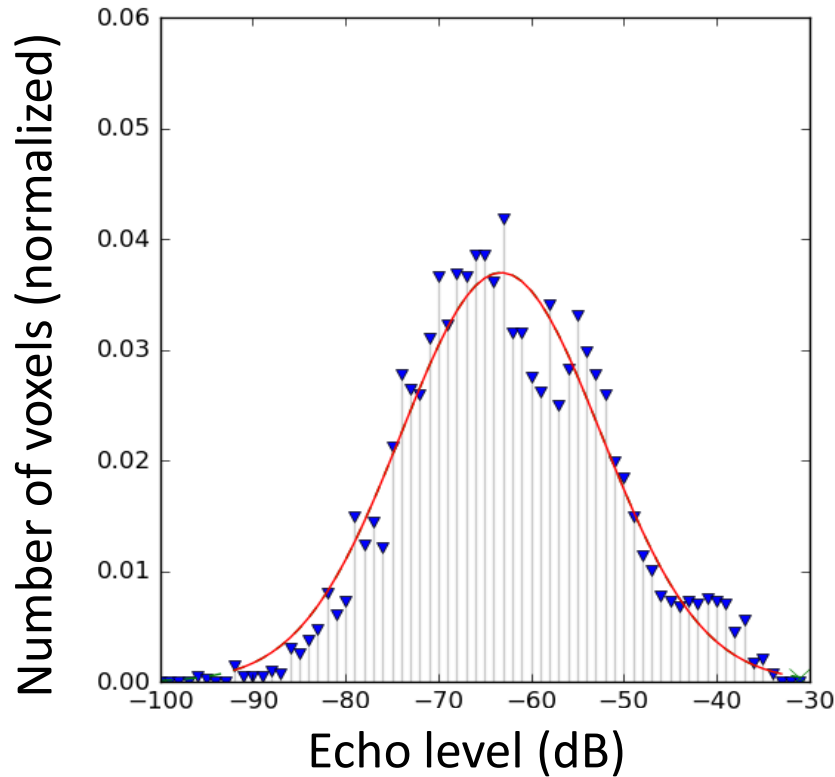
Application to humidity sensor device*

Passive humidity sensor 3D echo



* D. HENRY *et al.* *IEEE International Microwave Symposium*, 4-9 June 2017, Honolulu, Hawaii

Application to humidity sensor device*



* D. HENRY et al. *IEEE International Microwave Symposium*, 4-9 June 2017, Honolulu, Hawaii

Application to humidity sensor device*

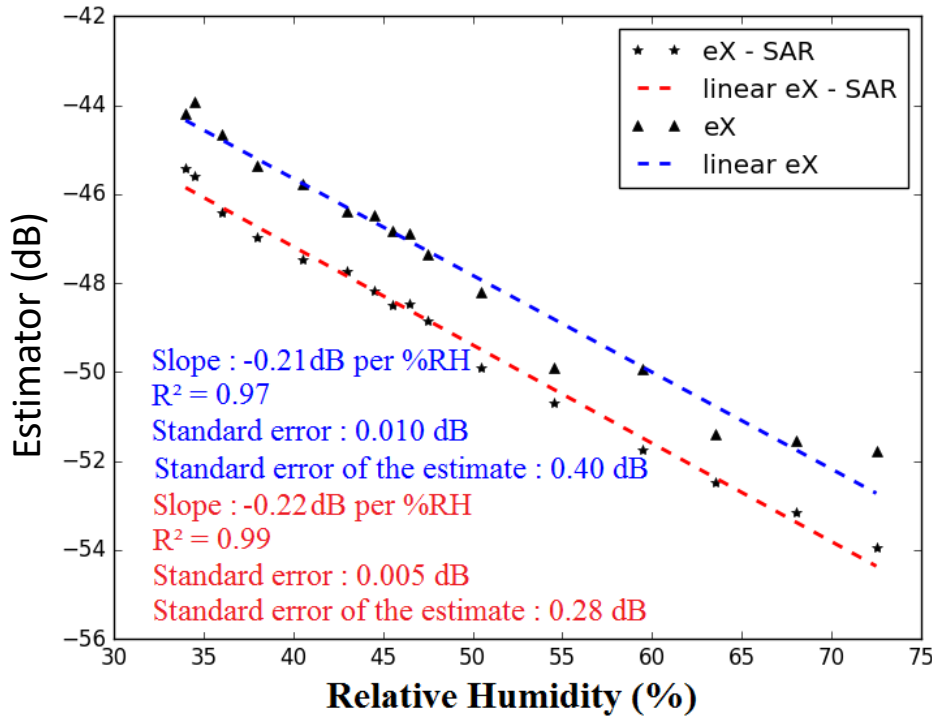
N : Total number of cells in the volume under consideration

$\{P_k, 1 \leq k \leq N\}$: Set of echo levels in the volume under consideration

M such as : $P_{M-1} = e_{Max}$

Proposed statistical estimators

At 10 m from the Radar



Maximum: $e_{Max} = \text{Max}\{P_k, 1 \leq k \leq N\}$

Arithmetic mean: $e_A = \sum_{n=0}^{M-1} \frac{P_n}{N}$

Weighted mean: $e_W = \sum_{n=0}^{M-1} P_n \cdot W_n$

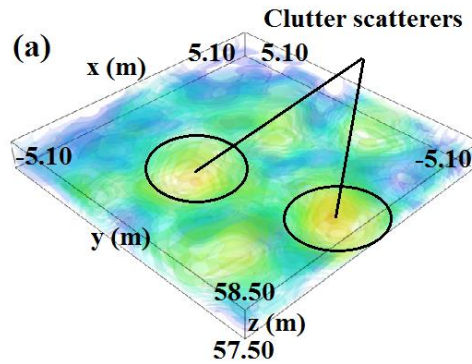
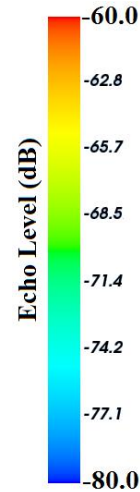
Shift: $e_\mu = \exp(\mu)$

Average: $e_X = \frac{1}{4} (e_{Max} + e_A + e_W + e_\mu)$

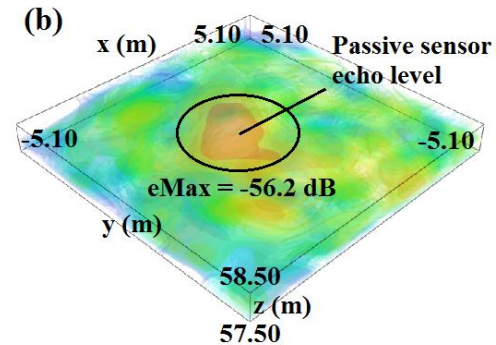
* D. HENRY et al. *IEEE International Microwave Symposium*, 4-9 June 2017, Honolulu, Hawaii

Application to humidity sensor device*

Indoor reading range of **58 meters**



Without sensor

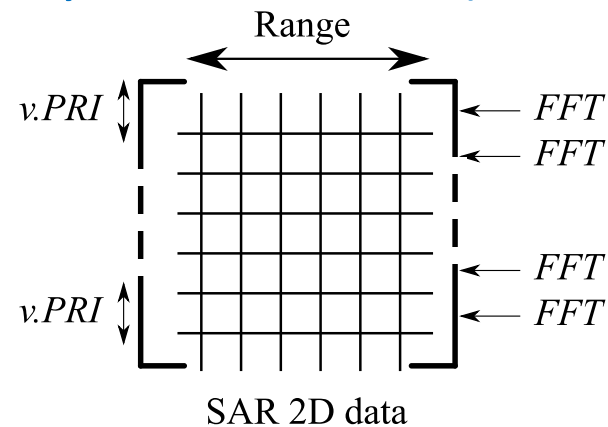
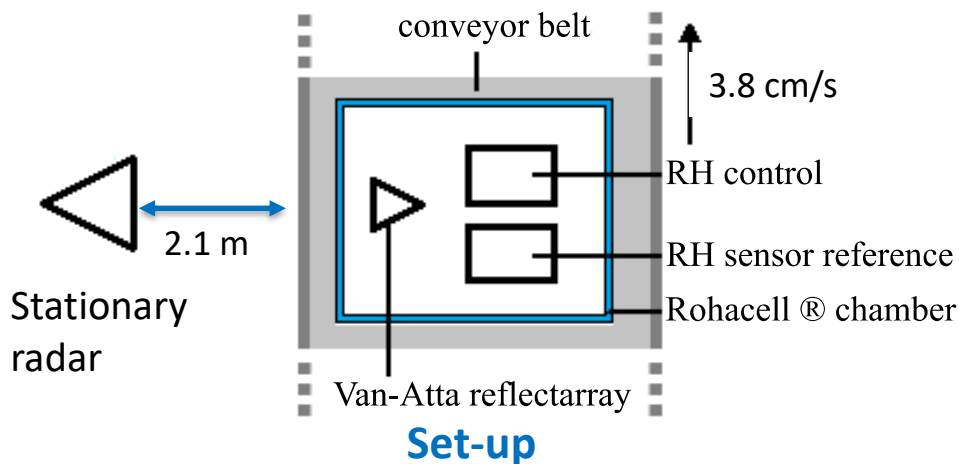


With sensor (RH=48%)

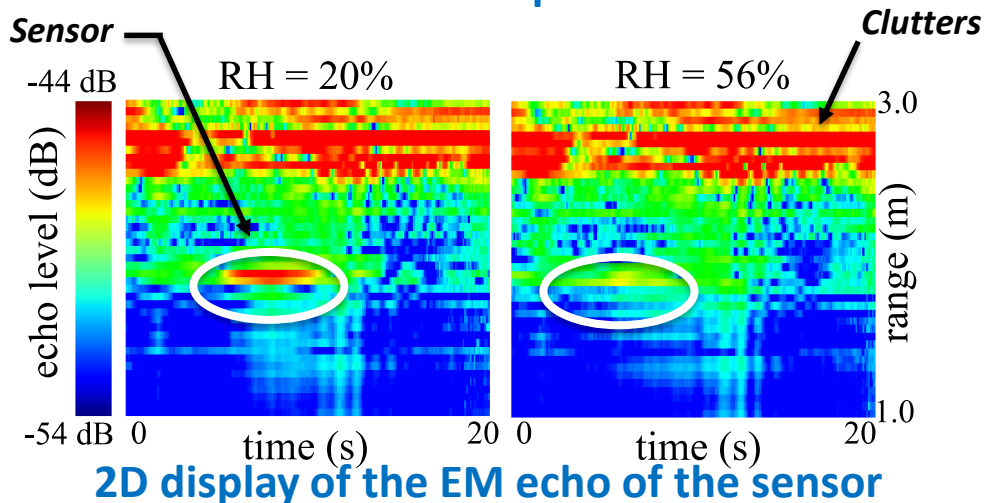
*D. HENRY *et al.* *IEEE International Microwave Symposium*, 4-9 June 2017, Honolulu, Hawaii

Application to humidity sensor device*

Detection of sensor in movement (on-the-fly measurement)



Generated 2D SAR data grid



Estimator for RH [20%-56%]	D (dB)	η (dB/%)	R^2	ϵ (%)
Emax – PRI = 0.1 s	9.0	-0.3	0.99	1.0
Emax – PRI = 1.0 s	9.4	-0.2	0.98	2.2
Emax – PRI = 2.5 s	10.5	-0.2	0.94	2.5
Emax – PRI = 3.0 s	10.5	-0.2	0.86	6.0

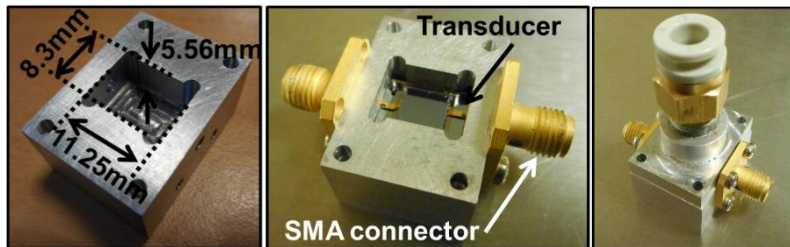
D : dynamic range
 η : sensitivity

R^2 : linearity (determination coef.)
 ϵ : precision (standard error)

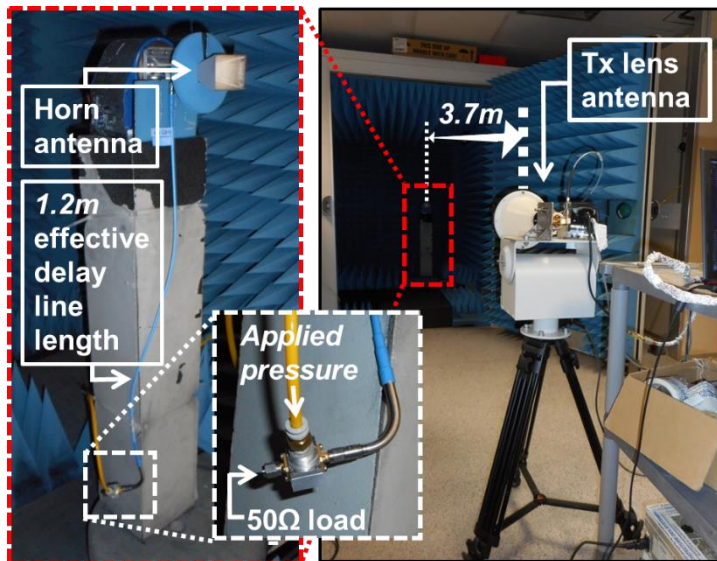
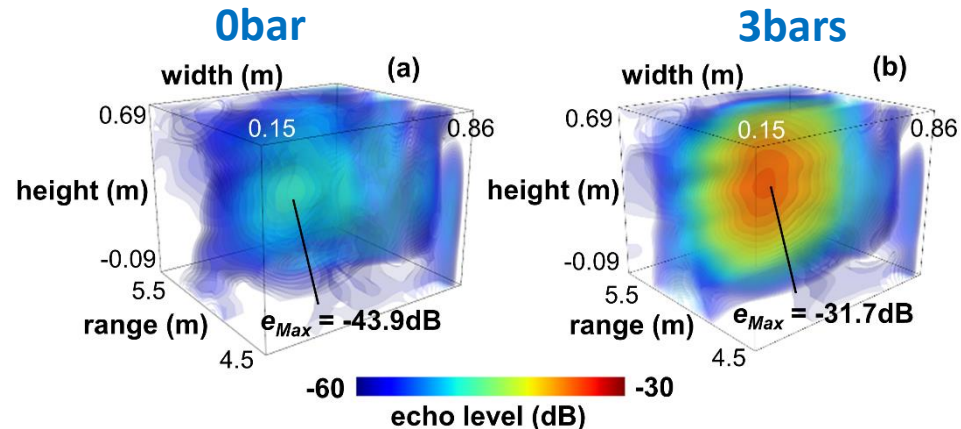
*D. HENRY et al., *IEEE Transactions on Microwave Theory and Techniques*, Vol. 65, No. 12, pp. 5345-5354

Application to pressure sensing device*

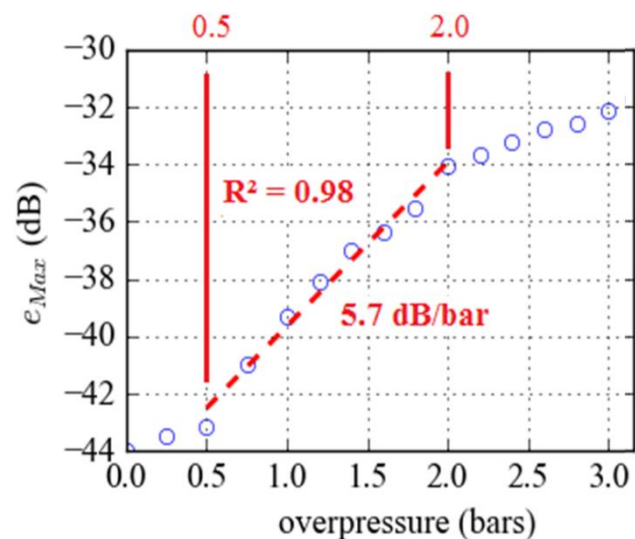
Indoor reading range of **3.7 meters** in anechoic chamber



Packaged sensor



Remote measurement set-up



*J. PHILIPPE et al., IEEE International Microwave Symposium , 10-15 June 2018, Philadelphia, USA

Conclusion

- Active radar Imaging technique + depolarizing & retrodirective passive sensors
 ➔ long-range remote measurement of physical quantity (up to 50 meters)
- Definition of statistical estimators for the physical quantity from 3D radar image
(normal distribution of EM echoes around the sensing device)

Conclusion and perspectives

- Active radar Imaging technique + depolarizing & retrodirective passive sensors
 ➔ long-range remote measurement of physical quantity (up to 50 meters)
- Definition of statistical estimators for the physical quantity from 3D radar image (normal distribution of EM echoes around the sensing device)

- Ongoing Works:
 - ✓ **Limitations** in terms of sensitivity, reading range and precision
 - ✓ **Electronic versus mechanical** beam scanning
 - ✓ Extension to the simultaneous interrogation of **multiple passive sensors**
 - ✓ Other solutions for generating the 3D radar image are possible

Acknowledgements

- For technical contributions to this work:

ARENAS BUENDIA Cristina, AUBERT Hervé, BOUAZIZ Sofiene, CHEBILA Franck, DEBOURG Emilie, DE PAOLIS Maria Valeria, HALLIL Hamida, HENRY Dominique, JATLAOUI Mehdi, PONS Patrick, RIFAÏ Ayoub, Manos TENTZERIS, THAI Trang and TRAILLE Anya.

- For past and current financial supports:

