WMC-6

Active FMCW Radar Imaging for Long-Range Wireless Passive Sensors

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de Toulouse Midi-Pyrénées

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Outline

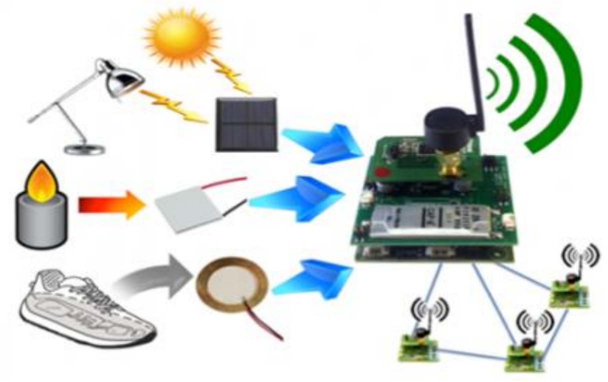
- **Context – RFID sensor technology**
- **Overview on batteryless and wireless EM Sensors**
- **Remote reading of passive EM sensors**

Context – RFID sensor technology

Context

- Internet of Things (IoT) : internet connected nodes with IP addresses

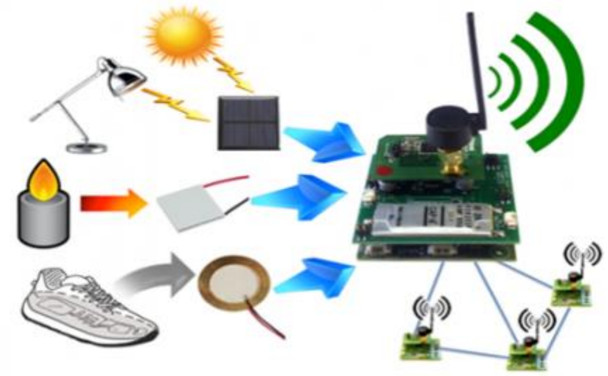
- Nodes with sensing, identification and communication capabilities



⇒ 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 $

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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

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Communication range : > 100 meters
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Cost in 2017 : 5 $ - 20 $

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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 $\Delta\upsilon$ of an electromagnetic descriptor

Sensing devices based on EM transduction

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⇩

variation $\Delta\upsilon$ 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	Key sensor descriptors
✓ High reading range (up to 100 m)	
✓ High measurement sensitivity	$\Delta\upsilon / \Delta\Phi$
✓ High linearity	R^2
✓ Large full-scale (or dynamic/total) range	$\max[\Phi] – \min[\Phi]$

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✓ High measurement resolution* (target : < 1%)	$\min[\Delta\Phi]/(\max[\Phi] - \min[\Phi])$

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✓ High measurement resolution* (target : < 1%)	$\min[\Delta\Phi]/(\max[\Phi] - \min[\Phi])$
✓ High measurement precision**	σ

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

** 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°C, T < -50°C, nuclear radiations, etc.)

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 cylindric 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

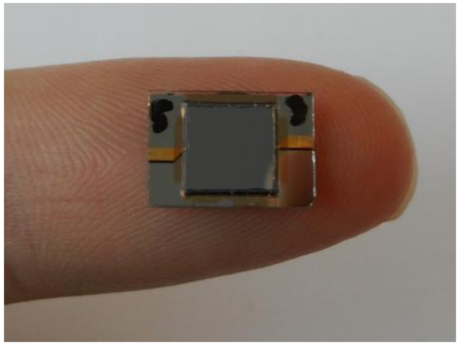
2009 : **First Fatigue Crack Sensor :** R Matsuzaki *et al., Smart Mat. Str*

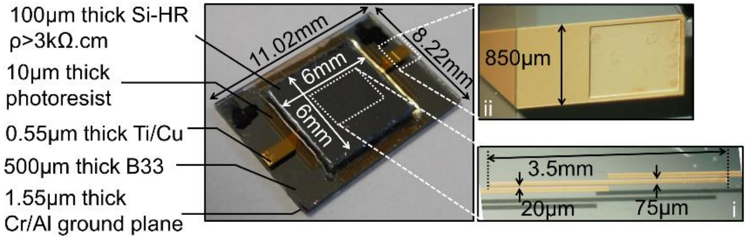
Modification of the electrical length of a patch antenna

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*





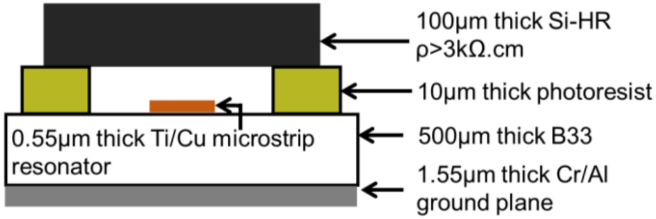
100µm thick Si-HR ρ>3kΩ.cm

10µm thick photoresist

0.55µm thick Ti/Cu

500µm thick B33

1.55µm thick Cr/Al ground plane



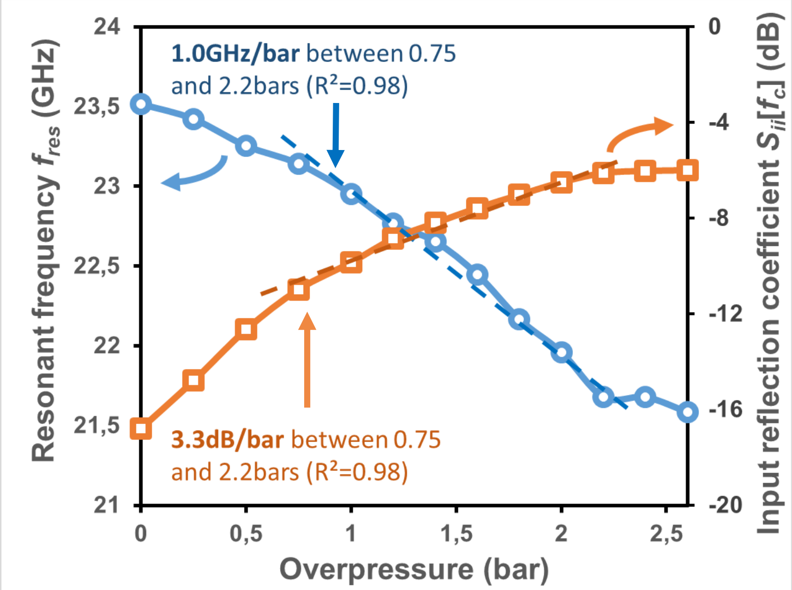
100µm thick Si-HR ρ>3kΩ.cm

10µm thick photoresist

0.55µm thick Ti/Cu microstrip resonator

500µm thick B33

1.55µm thick Cr/Al ground plane



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

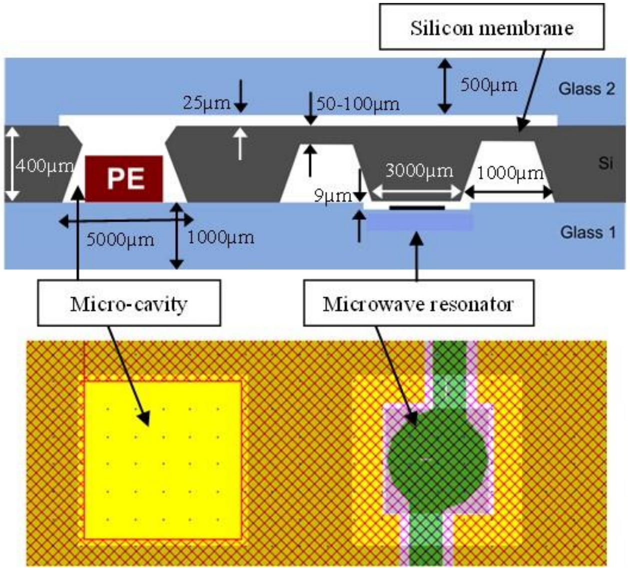
Dynamics of 4.9dB between 0.75 to 2.2bars

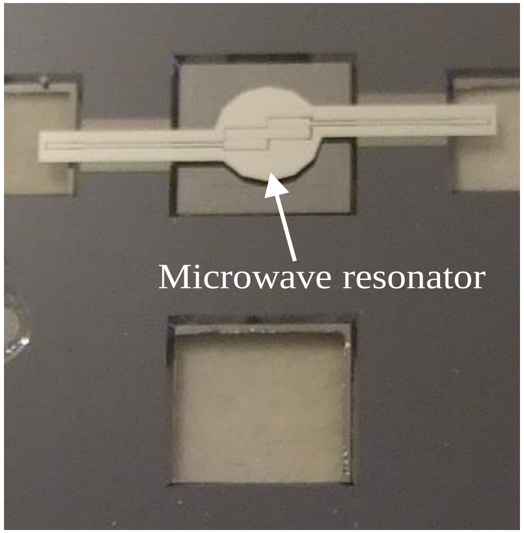
⇒ Interesting for radar measurement (radar frequency band of [22.8 – 24.8 GHz]

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

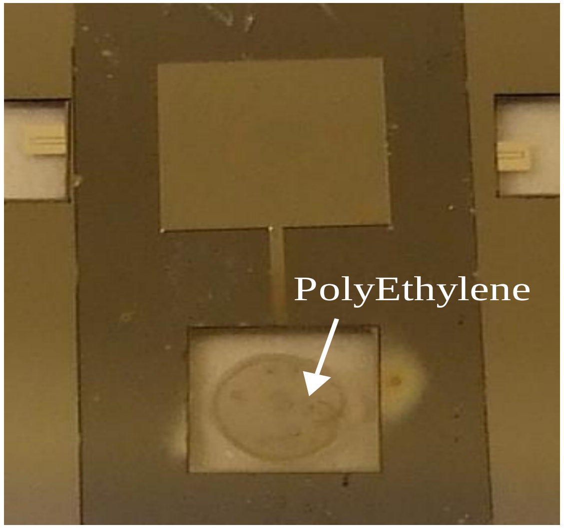
*J. PHILIPPE et al., EUROSENSORS 2017, Paris, France, 3-6 Sept 2017

Nuclear radiation passive EM sensing device*





Top side



Bottom side

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

Supported by : eDF European Commission

* 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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- **Use of FMCW radar technology (2010 →)**

More specifically:

→ millimeterwave FMCW radar**

→ 3D FMCW radar imaging (2015)***

→

Remote reading of passive EM sensors

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* 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 of misalignment between Tx-antenna and the sensor on measurements)**

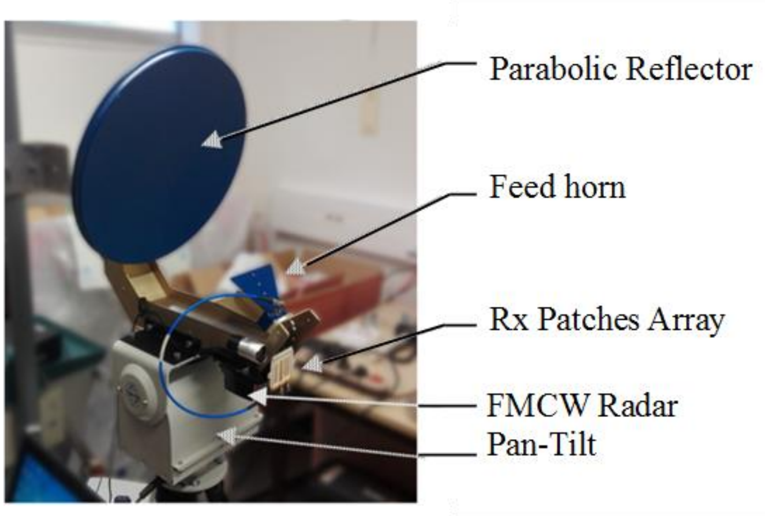
*D.HENRY *et al., IEEE International Microwave Symposium*, 17-22 May 2015, Phoenix, USA

**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

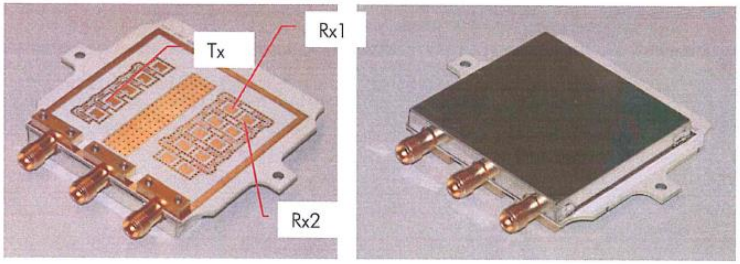
Tx-Antenna



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)



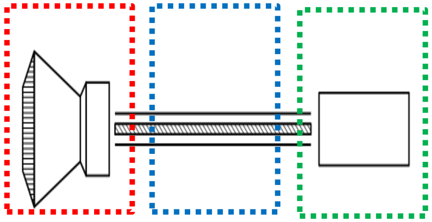
3-dB antenna characteristics and antenna gain :

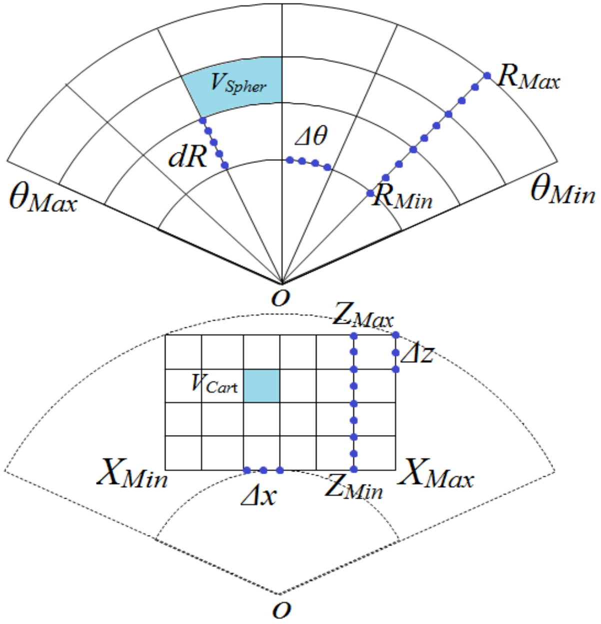
Rx1 : 60 deg Azimuth, 25 deg Elevation 10dBi gain
Rx2 : 70 deg Azimuth, 25 deg Elevation 9dBi gain
Tx : 2 deg Azimuth, 2 deg Elevation 33dBi gain

**From IMST GmbH*

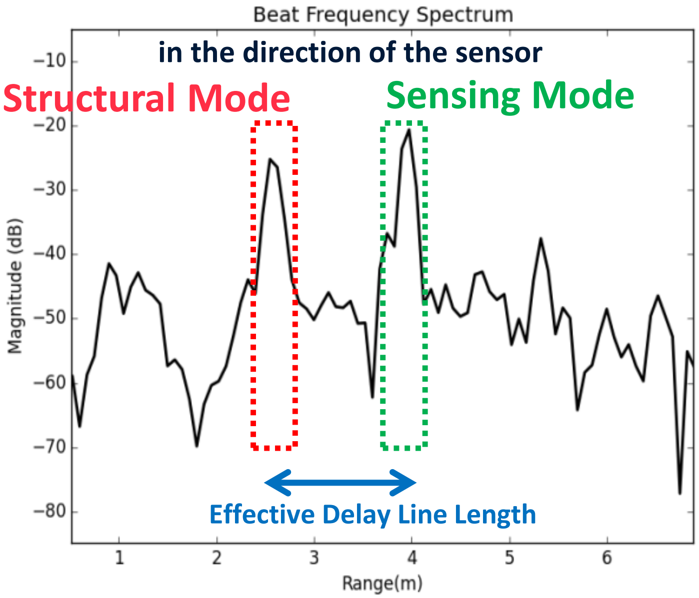
Radar imaging technique for passive EM sensors

Example of passive EM sensor





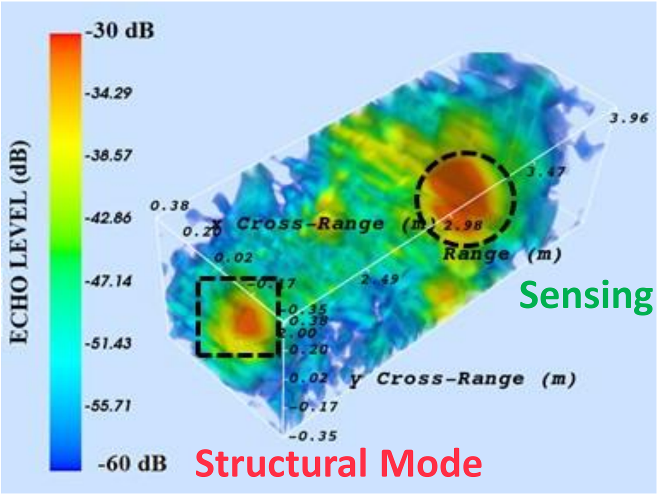
Beam scanning



in the direction of the sensor

Structural Mode **Sensing Mode**

Effective Delay Line Length



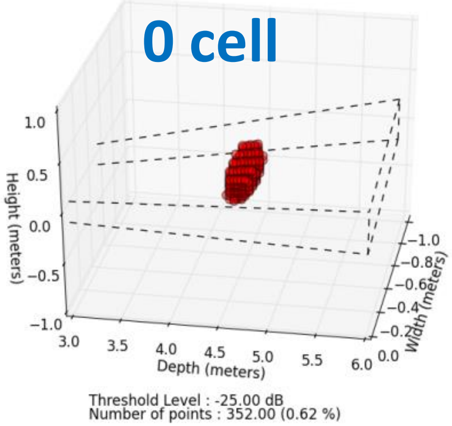
Sensing Mode

Structural Mode

Remote derivation of sensing device impedance*

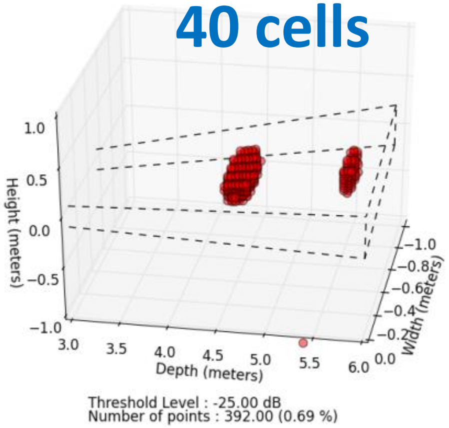
Z=50 Ω

0 cell



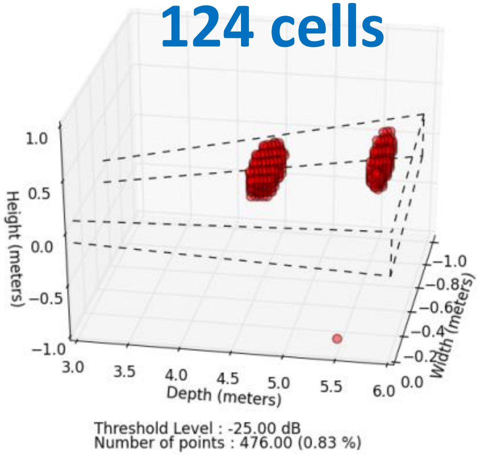
Z=30 Ω

40 cells



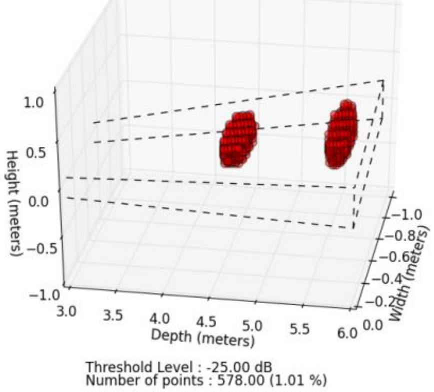
Z=17 Ω

124 cells



Z=0 Ω

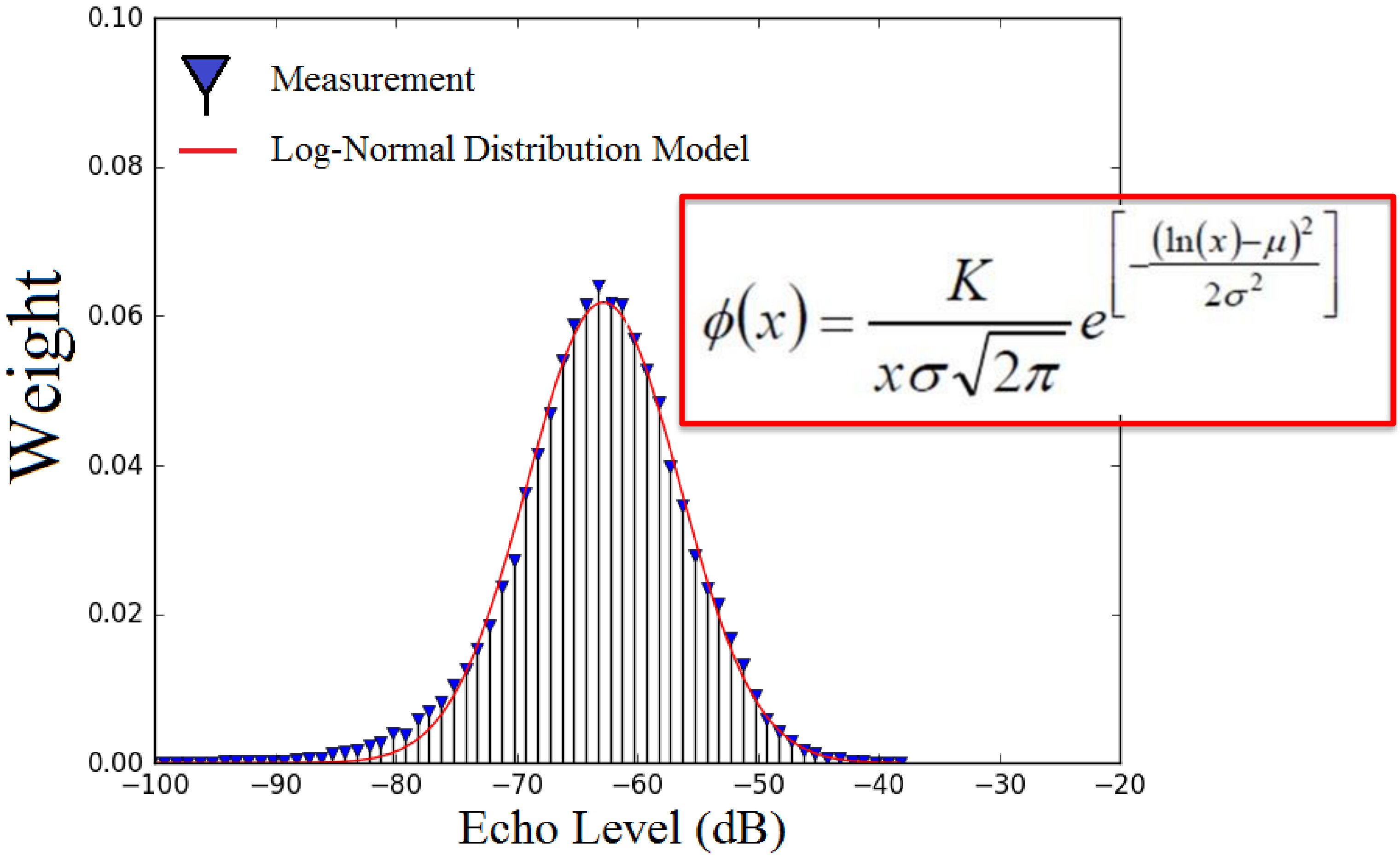
246 cells



*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



$$\phi(x) = \frac{K}{x\sigma\sqrt{2\pi}} e^{\left[-\frac{(\ln(x)-\mu)^2}{2\sigma^2}\right]}$$

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

Remote derivation of sensing device impedance*

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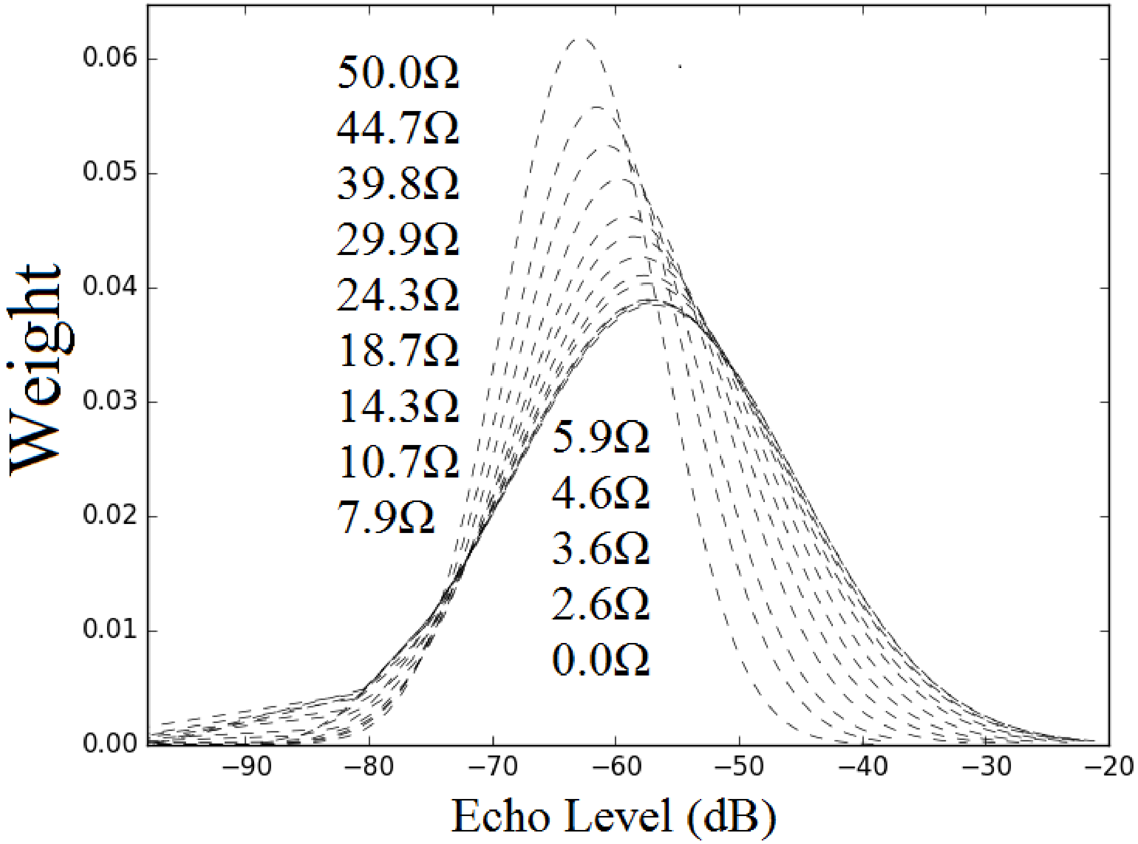


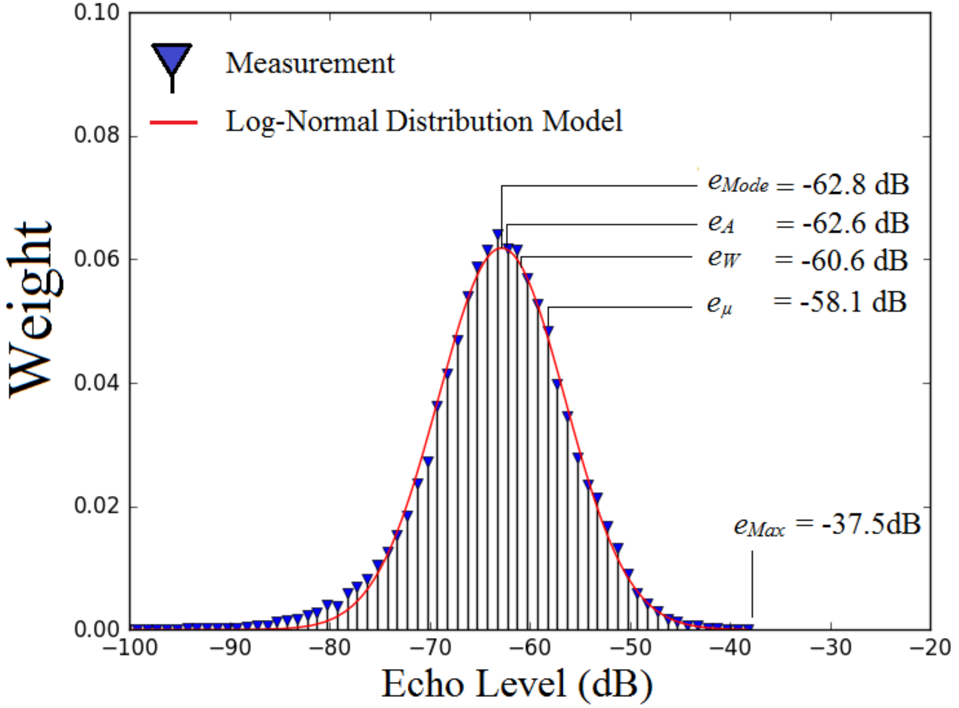
*D.HENRY *et al.*, EuMC 2016, London, UK, 4-6 Oct 2016

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

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

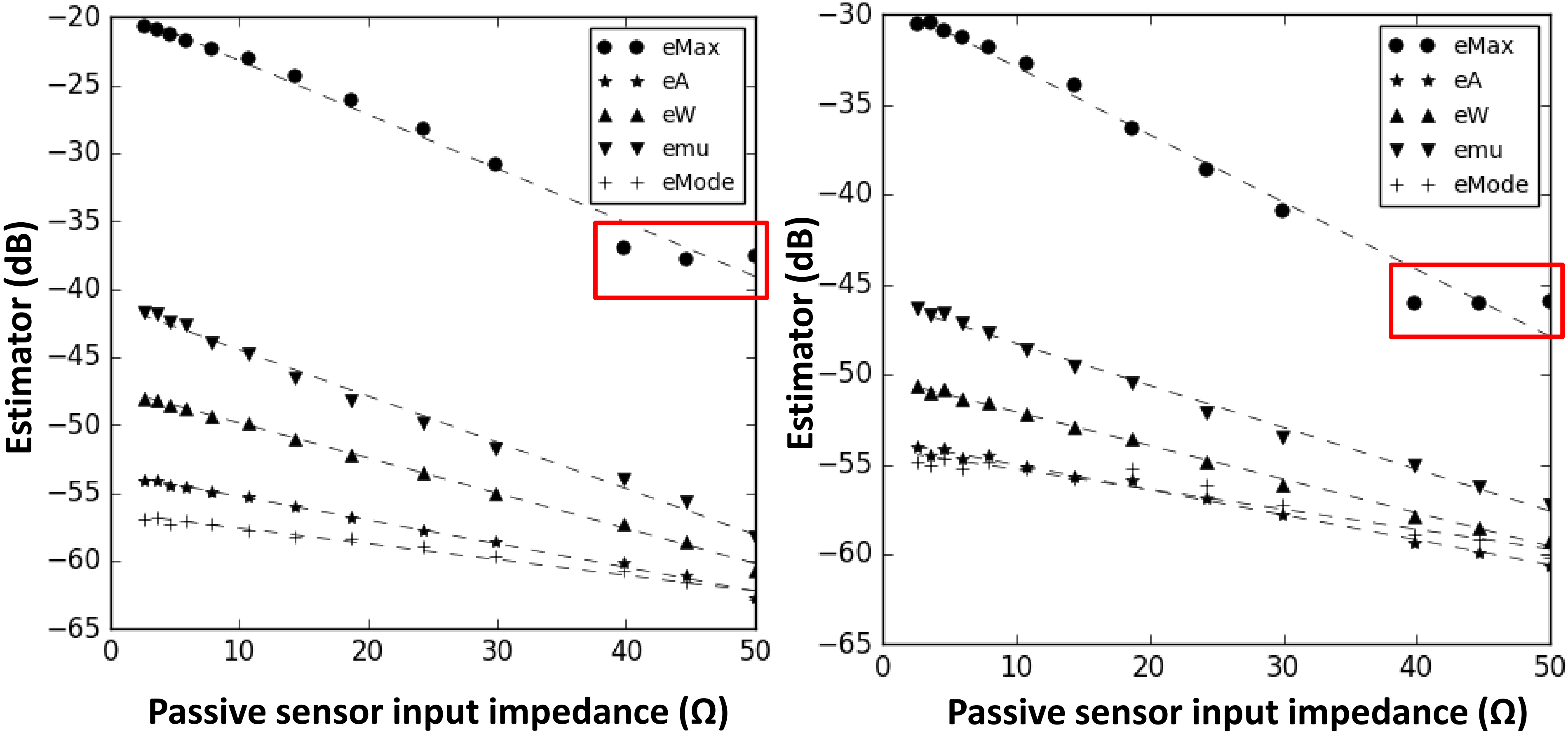
Shift: $e_\mu = \exp(\mu)$

*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

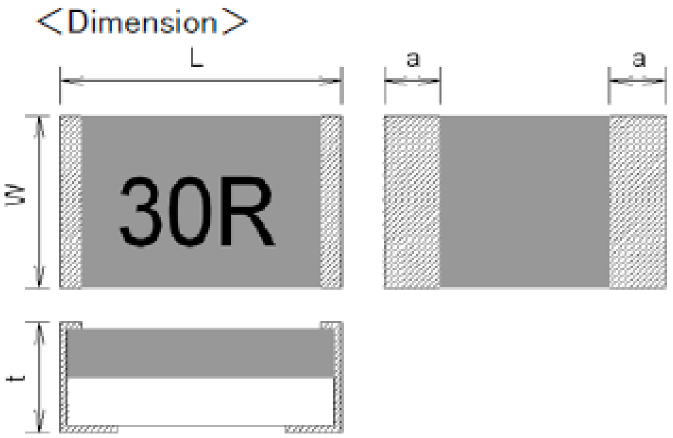
Application to temperature EM sensing device*

Antenna

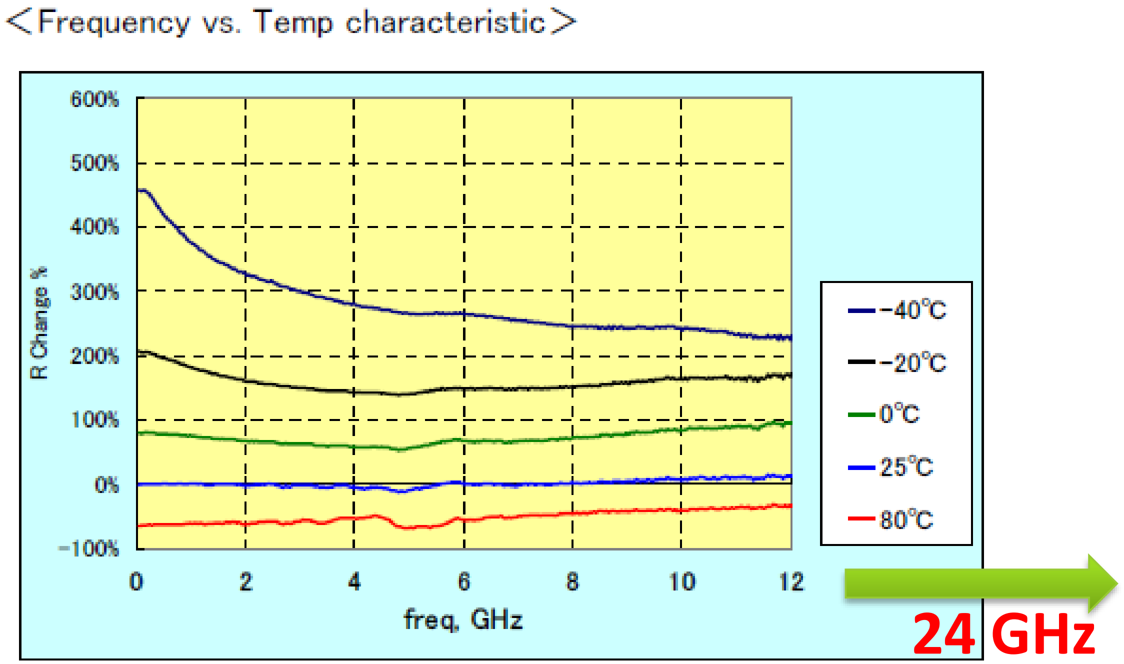
Thermistor

Delay line

Delay Line (Effective Length : 1.35 m)



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



SSM Thin Film Technology – SMT High Frequency Chip Thermistor 0805

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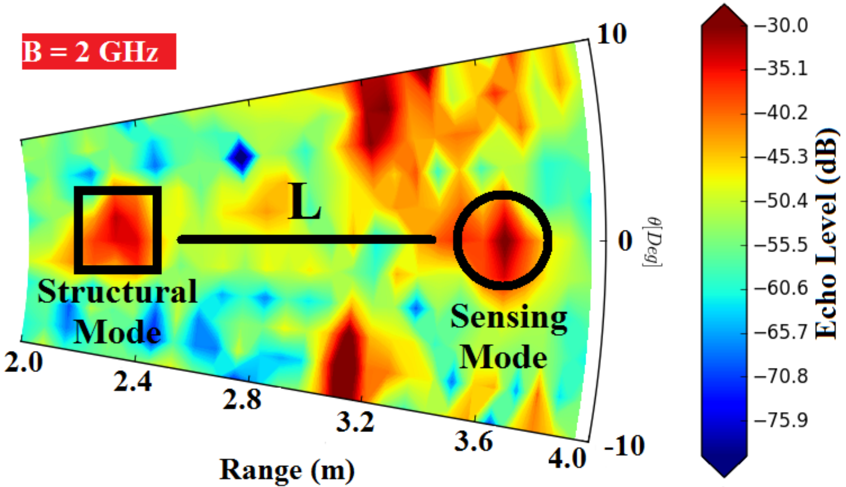
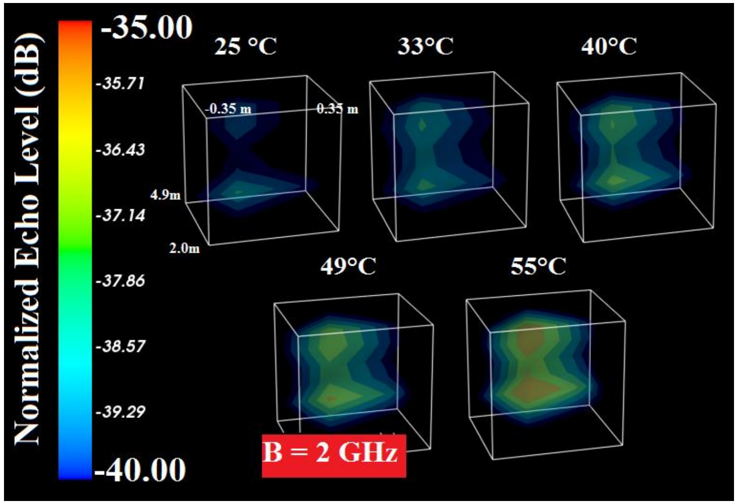
*D.HENRY *et al.*, *IEEE International Microwave Symposium*, 22-27 May 2016, San Francisco, CA, USA

Application to temperature EM sensing device*

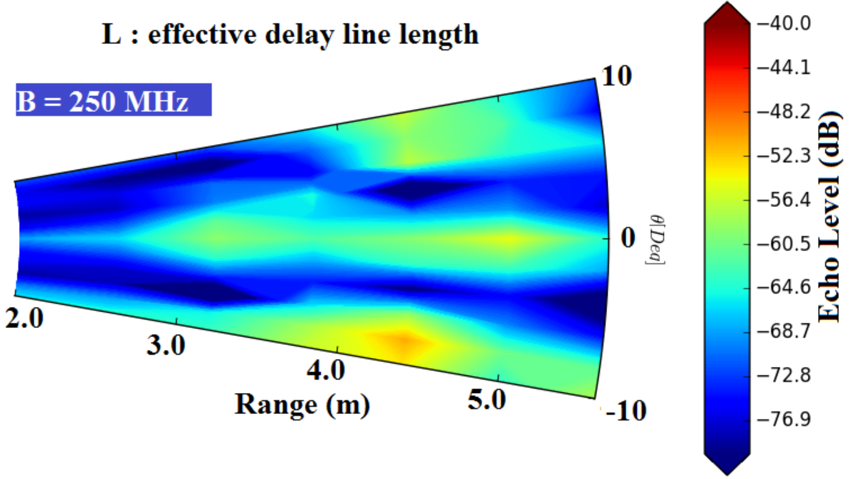
Theoretical depth resolution : **7.5 cm**

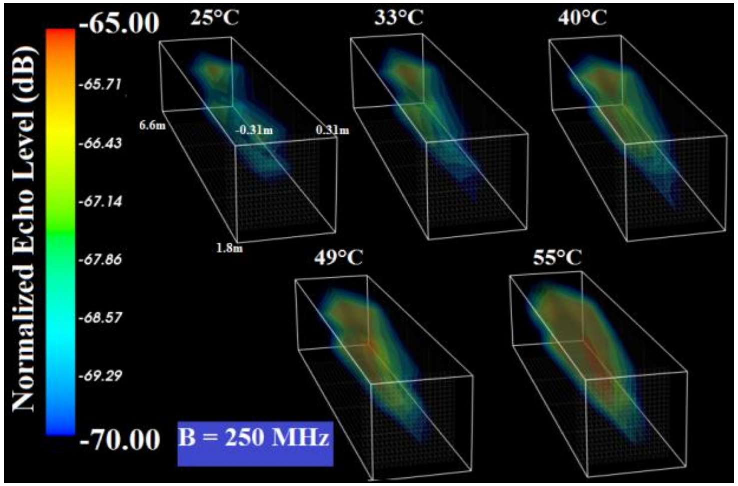




L : effective delay line length

Theoretical depth resolution : **60 cm**



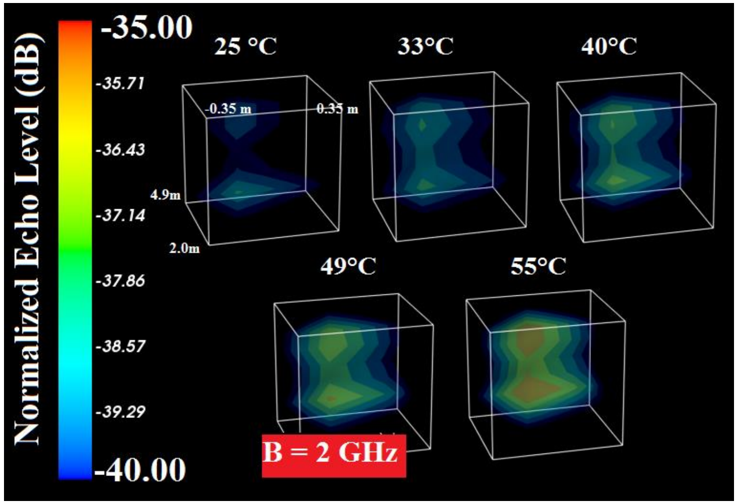


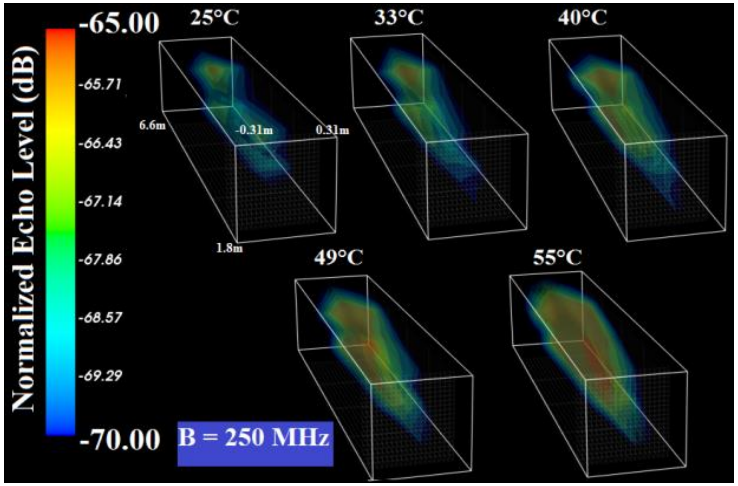
*D.HENRY *et al., IEEE Int.Microwave Symposium*, 22-27 May 2016, San Francisco, CA, USA

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.



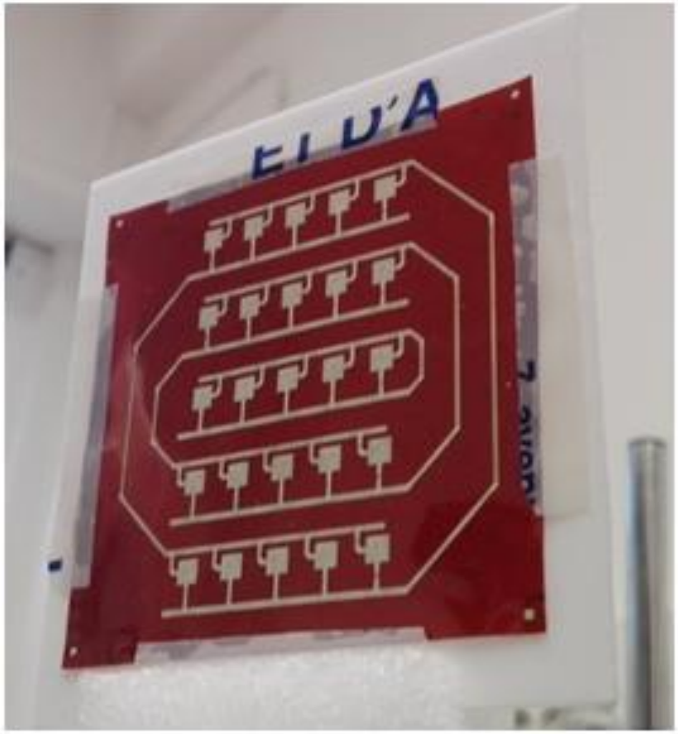


*D.HENRY *et al., IEEE Int.Microwave Symposium*, 22-27 May 2016, San Francisco, CA, USA

Application to humidity sensor device*

In collaboration with: ATHENA

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)

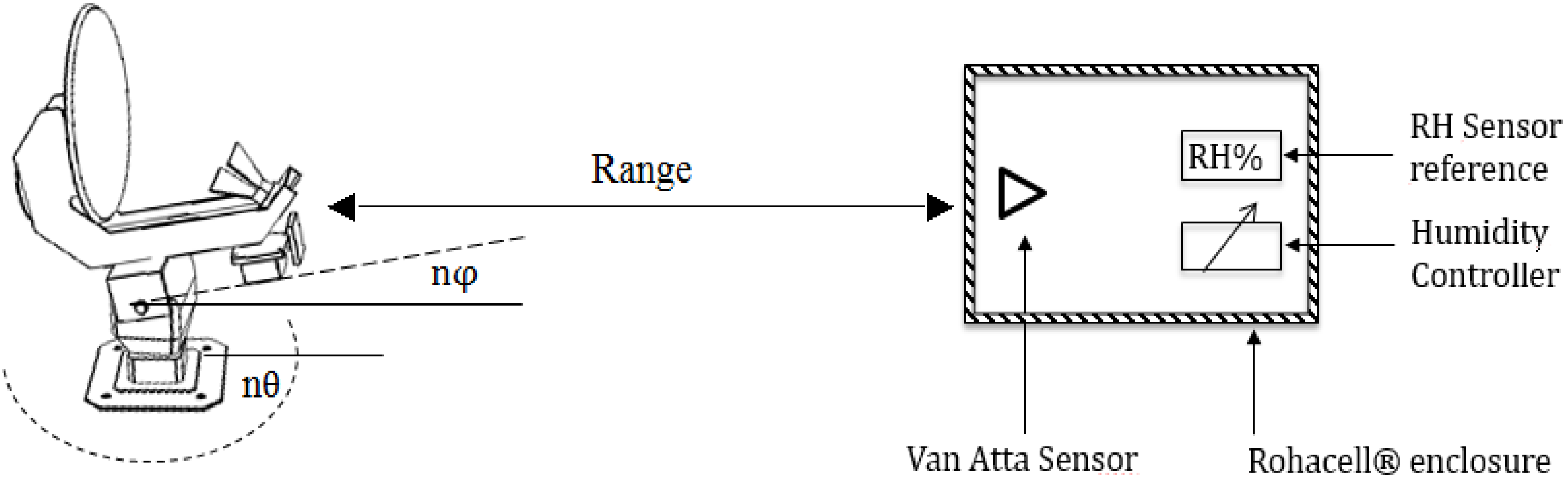
* D. HENRY *et al. IEEE International Microwave Symposium*, 4-9 June 2017, Honolulu, Hawaii

**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

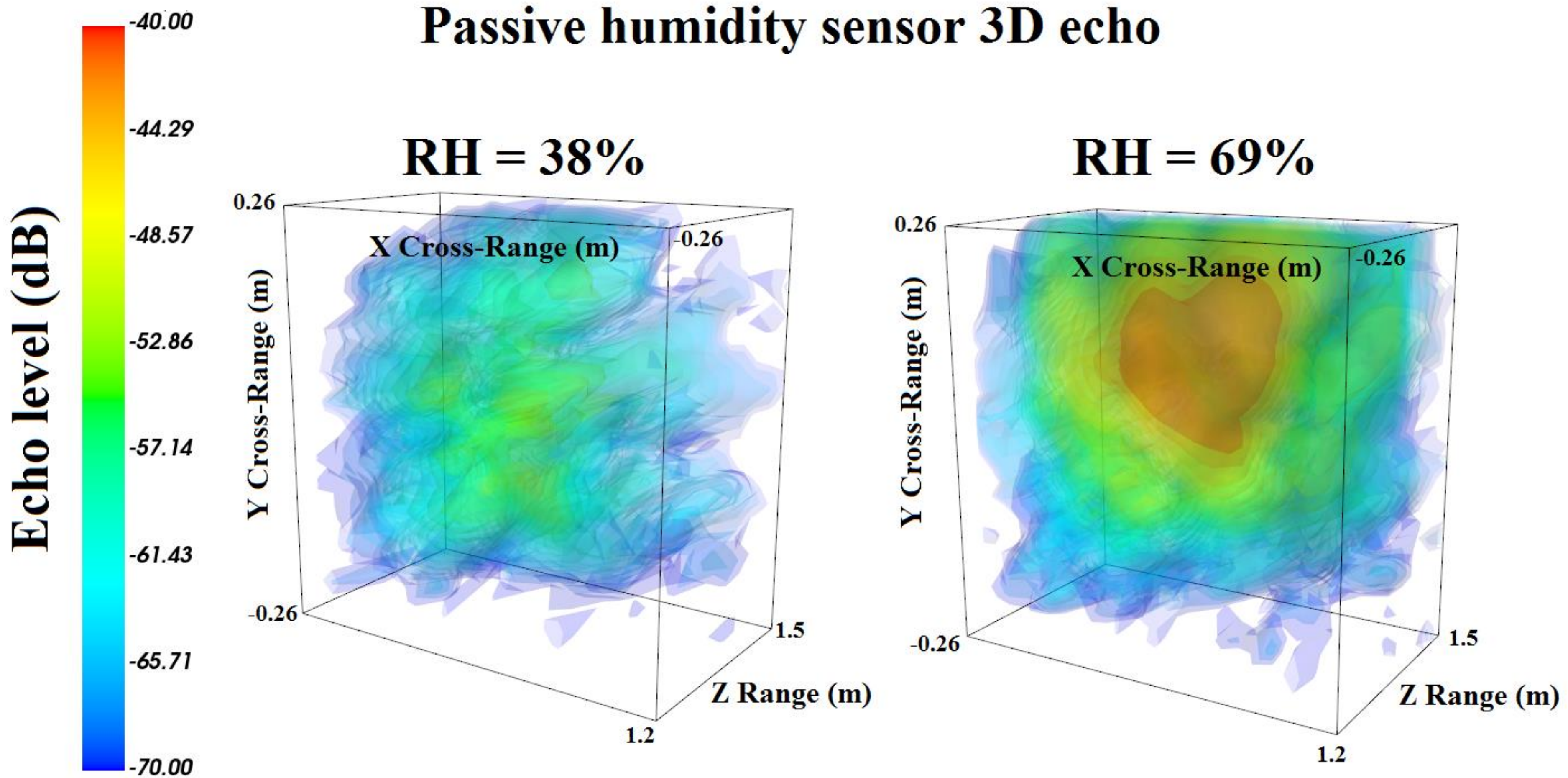


Recording of $n_{\vartheta}.n_{\varphi}$ beat frequency spectra

➡ 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*



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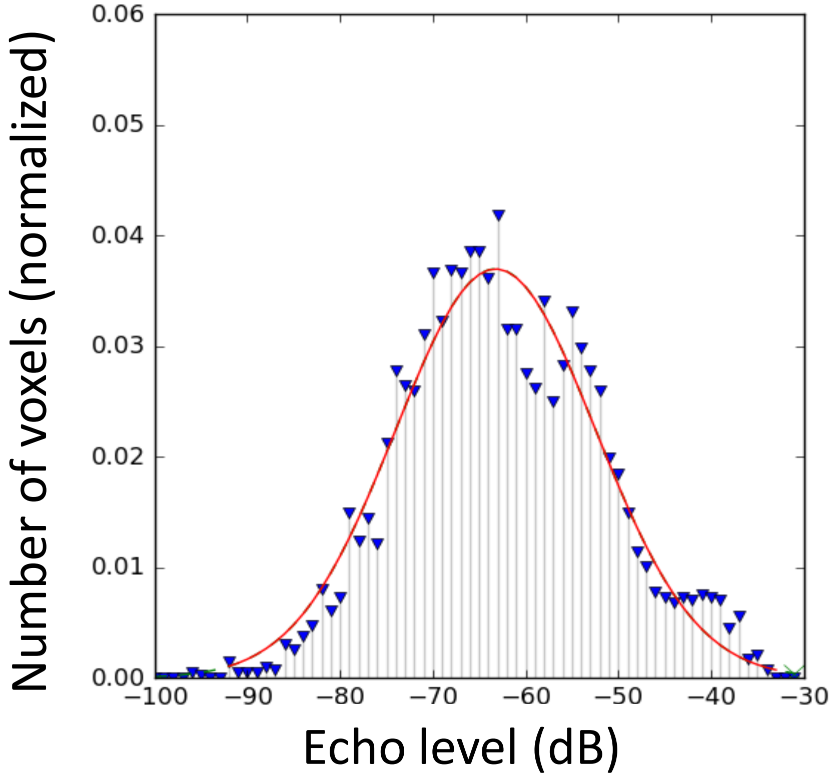
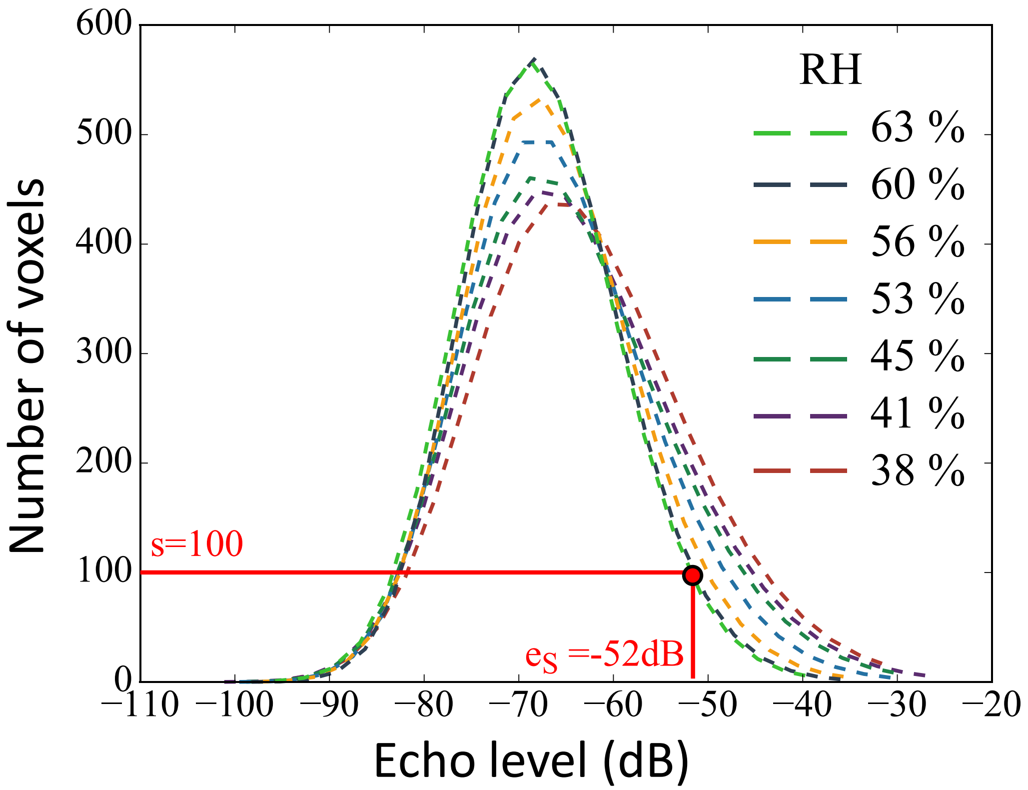
Application to humidity sensor device*





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

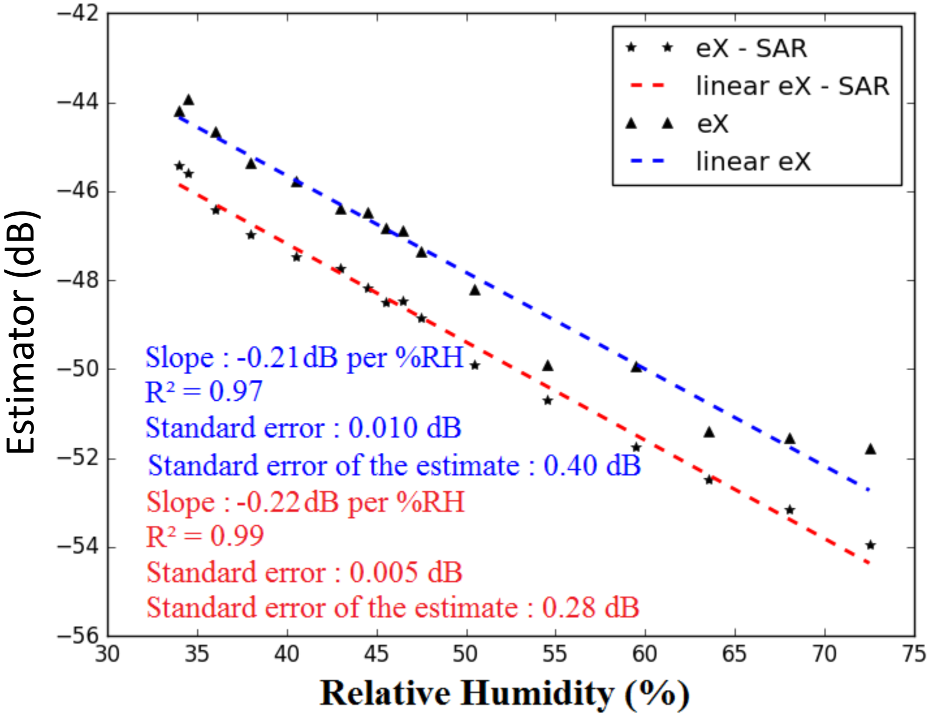
Application to humidity sensor device*

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

At 10 m from the Radar



Proposed statistical estimators

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

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

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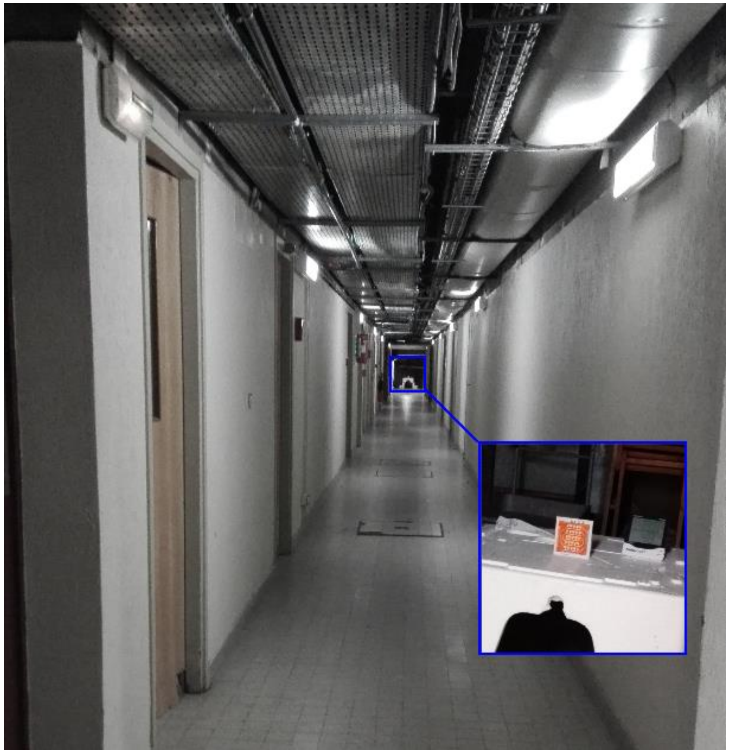
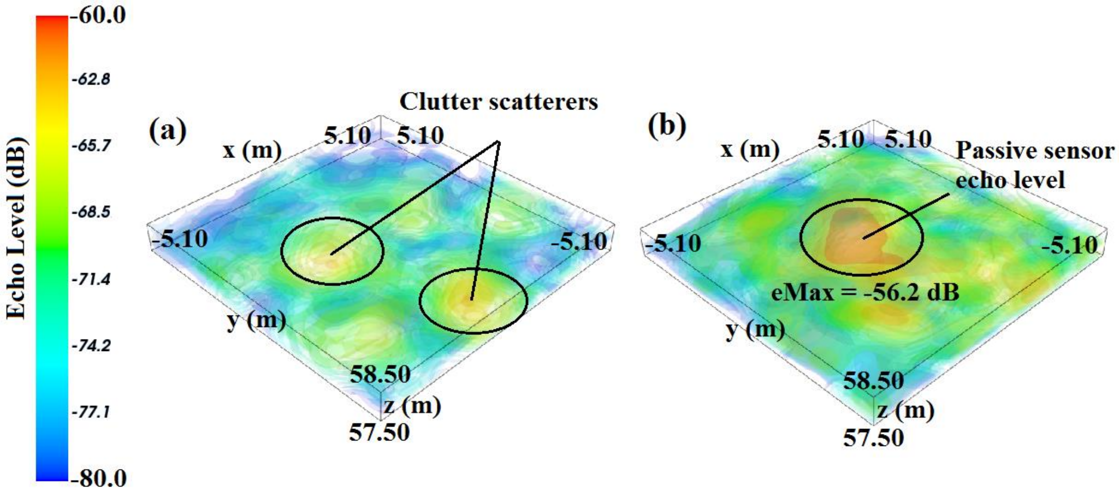
Application to humidity sensor device*

Indoor reading range of **58 meters**





Without sensor **With sensor (RH=48%)**

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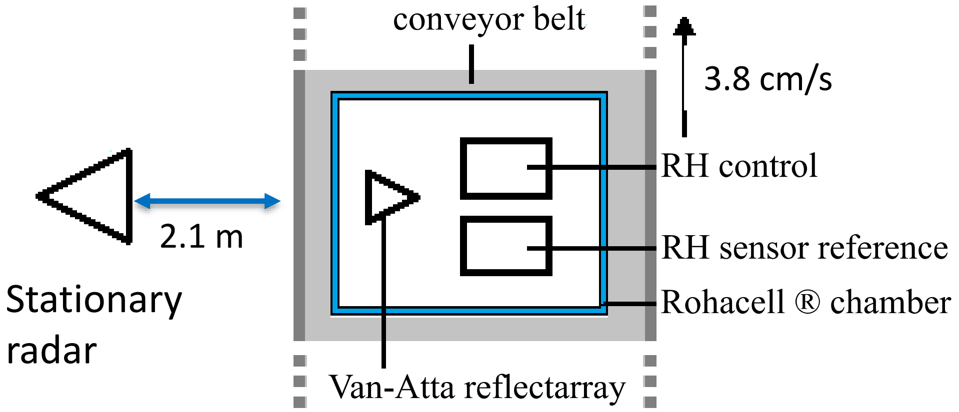
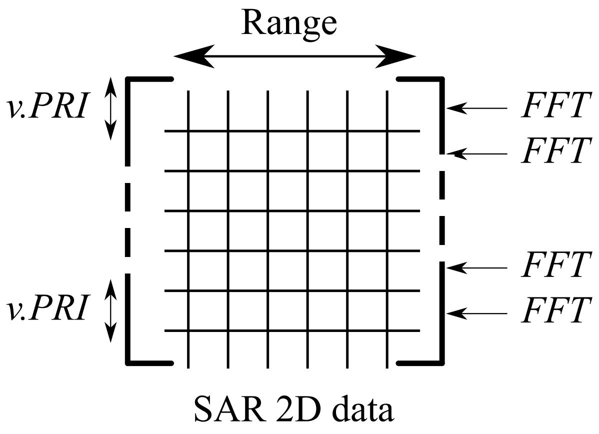
Application to humidity sensor device*

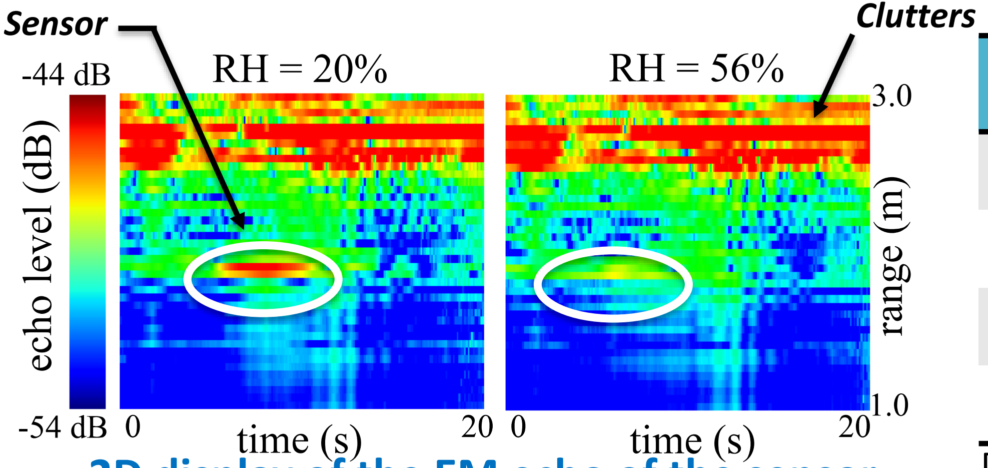
Detection of sensor in movement (on-the-fly measurement)



Set-up



Generated 2D SAR data grid



2D display of the EM echo of the sensor

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

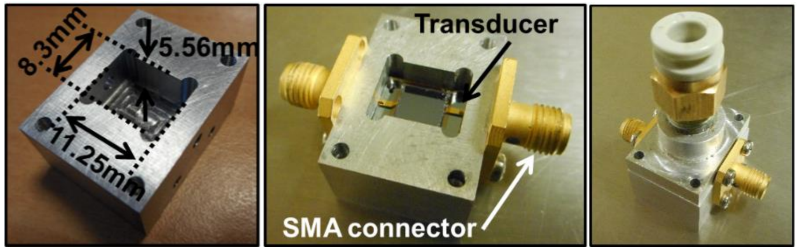
R^2: linearity (determination coef.)

ε: precision (standard error)

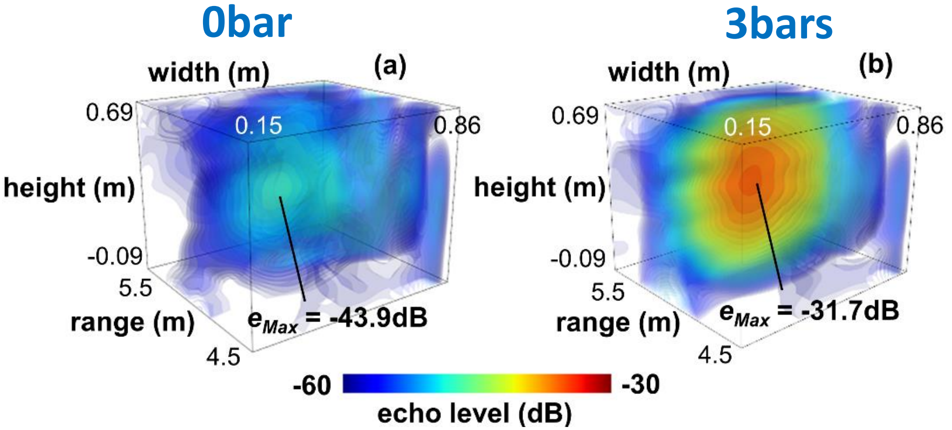
*D. HENRY *et al.*, *IEEE Transactions on Microwave Theory and Techniques*, Vol. 65, No. 12, pp. 5345-5354

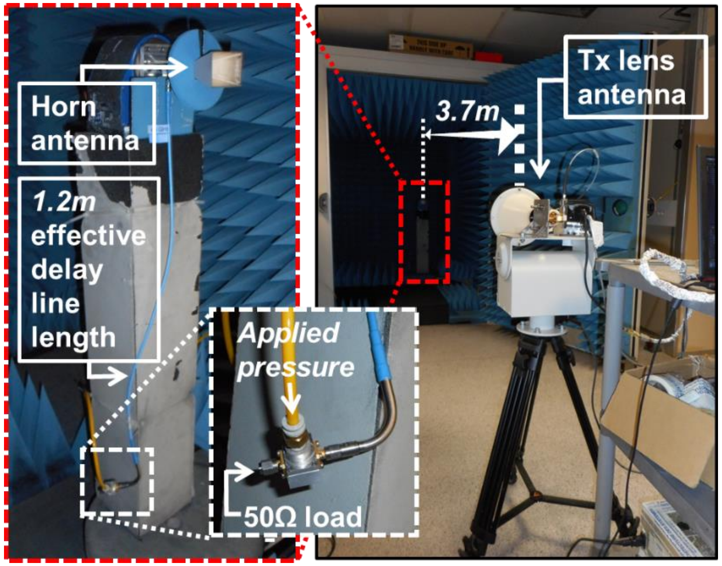
Application to pressure sensing device*

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

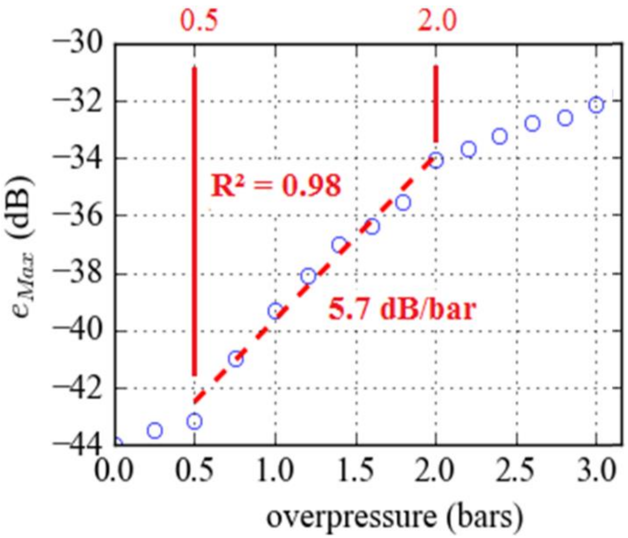


Packaged sensor





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

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