



# Millimeter-Wave Radar-on-Chip Based Techniques for Robust Contactless Vital Sensing and Smart Healthcare

*Ph.D. Candidate: **Ruochen Wu***

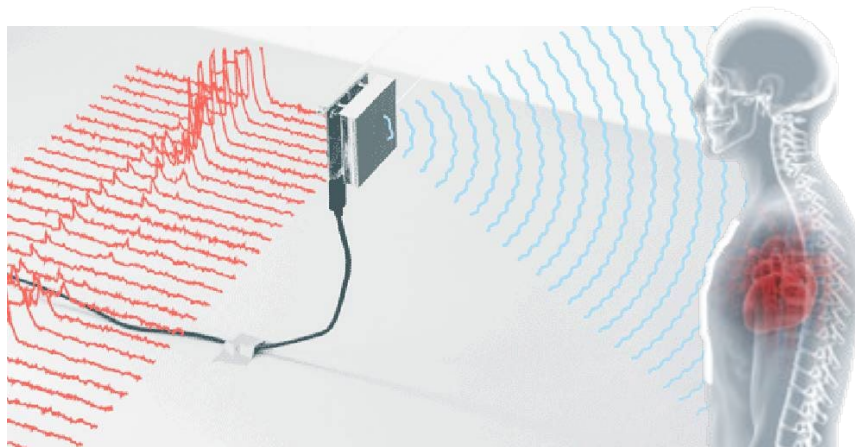
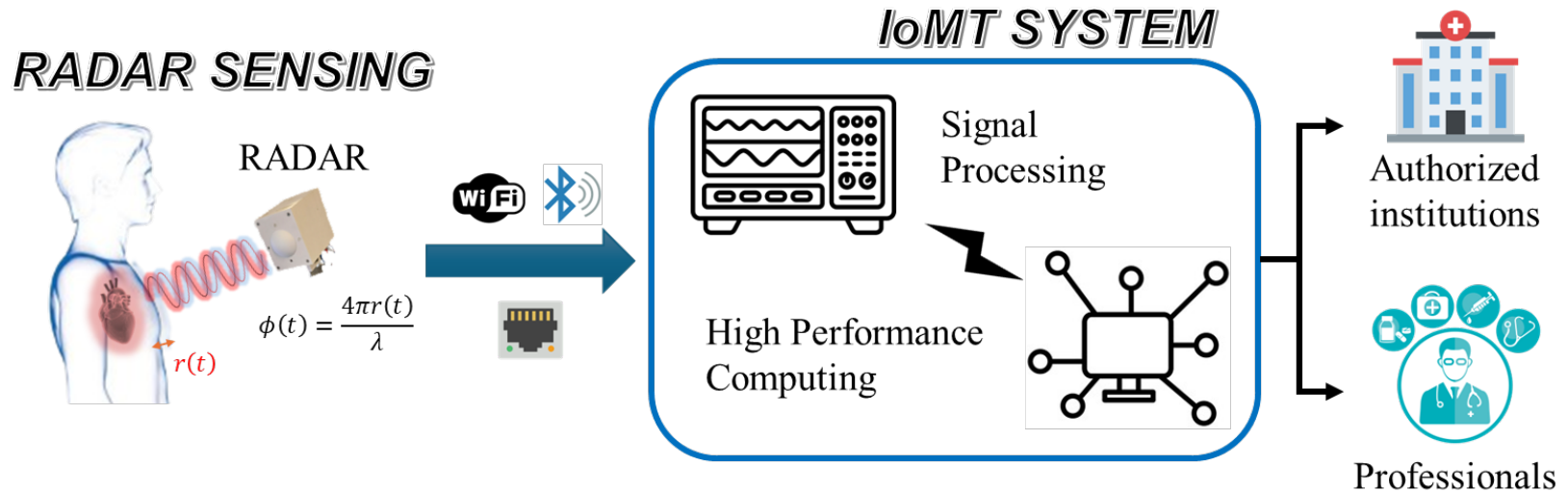
*Supervisor: Antoni Broquetas Ibars*

*Co-supervisor: Jordi J. Mallorquí Franquet*



- 
- 1. Motivation
  - 2. Objectives
  - 3. Theory: FMCW radar
  - 4. Main contributions:
    - (0) Radar characterization for vital sensing
    - (1) Novel technique for biometric sensing
    - (2) Autonomous beam orientation
    - (3) Eyelid dynamics characteristics
    - (4) New dataset of radar vital signals
  - 5. Conclusions

# Motivation (I)



High Sensitivity  
to Micro-Motions

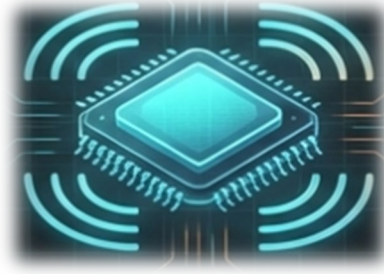
Local  
Processing

- **Paradigm shift in smart healthcare:** enables continuous, proactive, and unobtrusive care.
- **Promising impact:** enhances quality of life and optimizes hospital resources.

# Motivation (II)



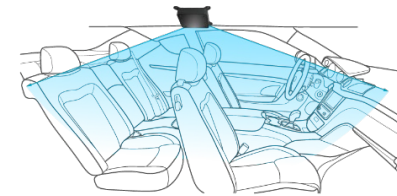
Burn patients



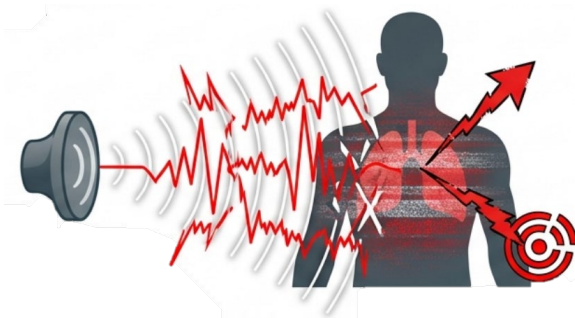
Newborn care



Long term care



In-cabin  
monitoring



## MAIN CHALLENGES

Low signal-to-interference-plus-noise ratio (SINR)

Difficulty of cardiac signal processing

Scarcity of radar vital signals and datasets

## Motivation (III)

- **RADAR configurations**
- Frequency bands - *Industrial, Scientific, and Medical (ISM) bands*

Continuous Wave (CW) Doppler  
NO range info

Ultra-Wideband (UWB) pulse  
Short range, susceptible to  
interference

Stepped-Frequency Continuous  
Wave (SFCW)  
Low acquisition

**Frequency-Modulated  
Continuous Wave (FMCW)**  
Compact + range info

24 GHz (ISM)  
 $\lambda = 12$  mm,  $\mu\text{m}$ -blind

60 GHz (ISM)  
 $\lambda = 5$  mm,  $O_2$  absorption

77 GHz  
 $\lambda = 3.9$  mm,  
automotive focus

**120 GHz (ISM)**  
 $\lambda = 2.4$  mm,  $\mu\text{m}$ -sensitive

## ■ Algorithms

FFT

Efficient for distance resolution

Limited to the frequency domain, losing temporal details and the dynamic HRV

Wavelet  
Transform

Good performance in noise filtering and vital signal separation

Relies on manual selection of a fixed basis function

EMD/VMD

Effective in separating breathing and heartbeat patterns

Prone to mode mixing and poor real-time performance

AI models

Effective in complex cases with low SINR

Massive amounts of training data to learn, high computational cost and lack of interpretability

**Current algorithms lack robustness against individual physiological differences!**

- **Requirements:**
- For radar:
  - High sensitivity to body motions
  - Immune to nearby objects
  - Reduced size & weight
  - Low cost and easy to deploy
- For technique:
  - Optimal SINR
  - Robust extraction of vital information
    - Respiratory rate (RR) / Heart rate (HR)
    - HRV
    - Cardiac cycle period



# Objectives (II)

- 1. Optimization and application of a high-frequency Radar System-on-Chip (RSoC)

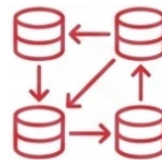


- 2. Development of an advanced algorithm for biometric sensing



- 3. Solving practical problems:

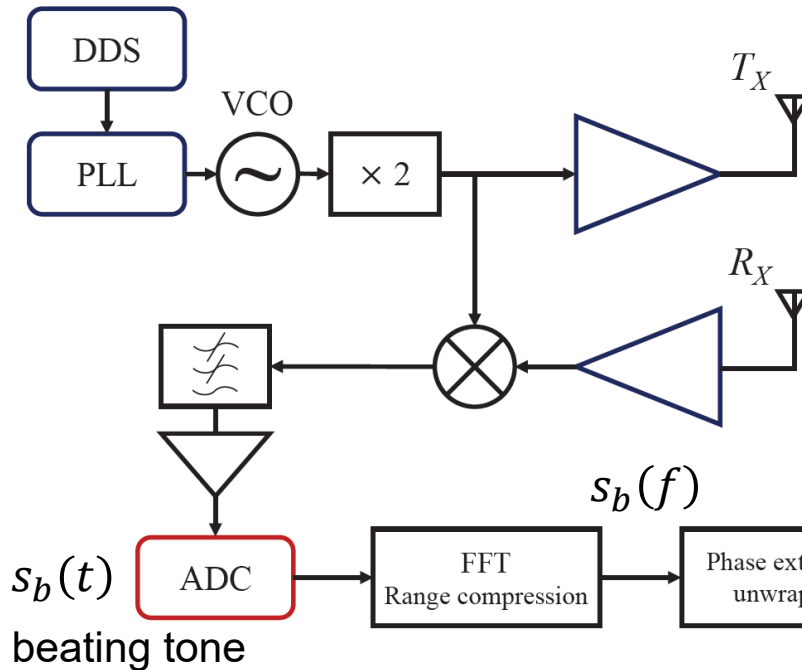
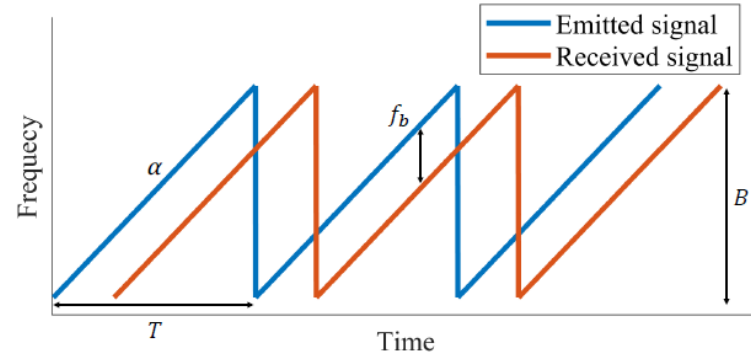
- Radar beam orientation
- Data scarcity
- ...



# FMCW Radar Principal

$$f_b = -\frac{2B}{T_{Chirp}c} r$$

→ Distance of the target

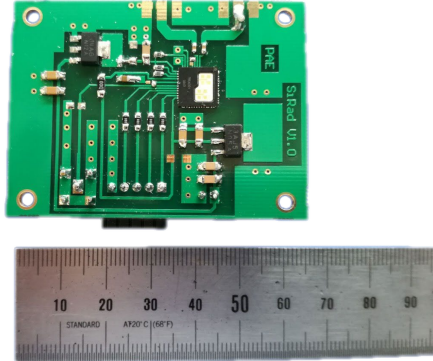


$$\begin{aligned} \phi_b &= -2\pi f_0 \frac{2r}{c} \\ &= -2kr \end{aligned}$$



Important for  
**displacement**  
obtention

## Radar Characterization & Optimization (I)



120 GHz RSoC  
(TRX\_120\_001)



Teflon dielectric lens to  
enhance the radar spatial  
resolution and sensitivity

Parameter	Value
Center Frequency ( $f_0$ )	122.5 GHz
Radar Nominal Bandwidth <sup>1</sup> ( $B$ )	1 GHz
Antenna Beamwidth ( $\theta_{3dB}$ )	2°
Radar Range Resolution ( $\Delta r$ )	$\frac{c}{2B} = 150$ mm
Wavelength ( $\lambda$ )	$\frac{c}{f_0} = 2.449$ mm
Chirp Repetition Period ( $T_{frame}$ )	3 ms
Chirp Slope Time ( $T$ )	1.5 ms

1: Specified by the industrial, scientific, and medical (ISM) band.

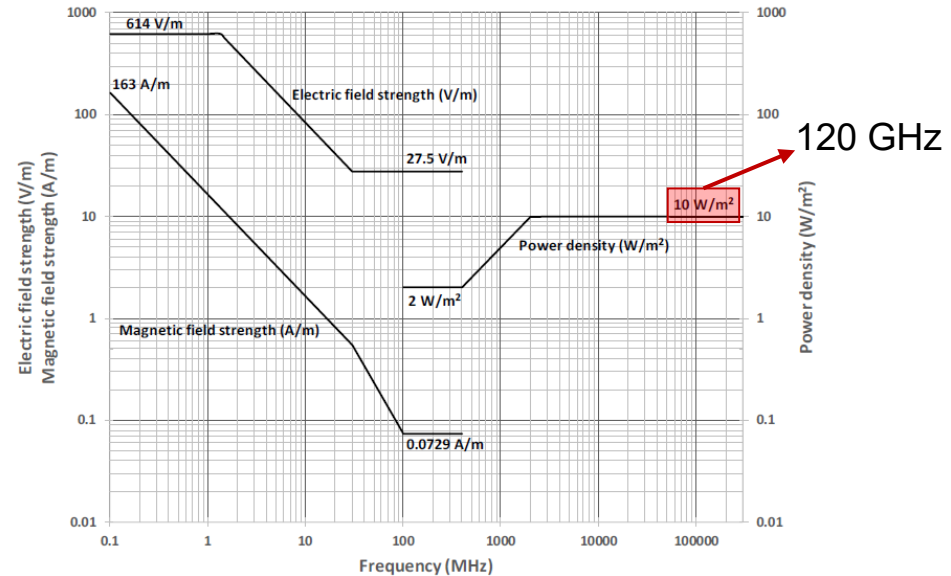
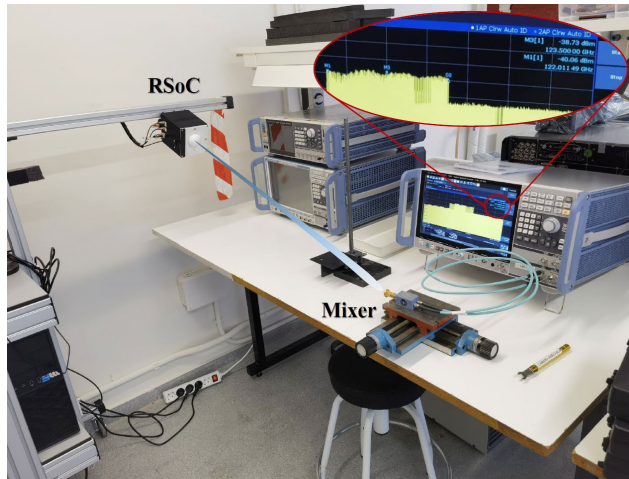
In our experimental setup, a radar bandwidth of 3 GHz was configured.

## Radar Characterization & Optimization (II)

### ■ Safety

IEEE Std C95.1-2019

IEEE Standard for Safety Levels with Respect to Human Exposure to Electric, Magnetic, and Electromagnetic Fields, 0 Hz to 300 GHz



$$P_{RF} = -38.73 + 26.658 = -12.072 \text{ dBm} = 6.206 \times 10^{-5} \text{ W}$$

$$A_s = \frac{G\lambda^2}{4\pi} = \frac{10^{0.7} \times (2.449 \times 10^{-3})^2}{4\pi} = 2.392 \times 10^{-6} \text{ m}^2$$

$$S_{patient} = \frac{P_{RF}}{A_s} = 2.594 \text{ mW/m}^2$$

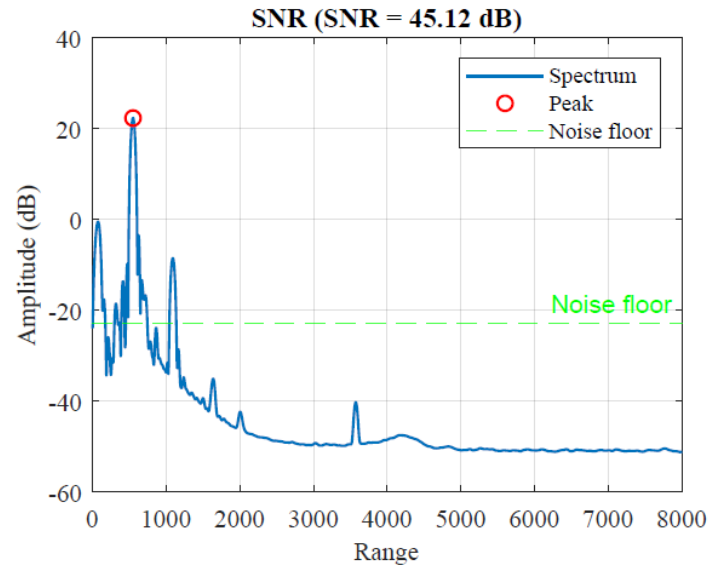
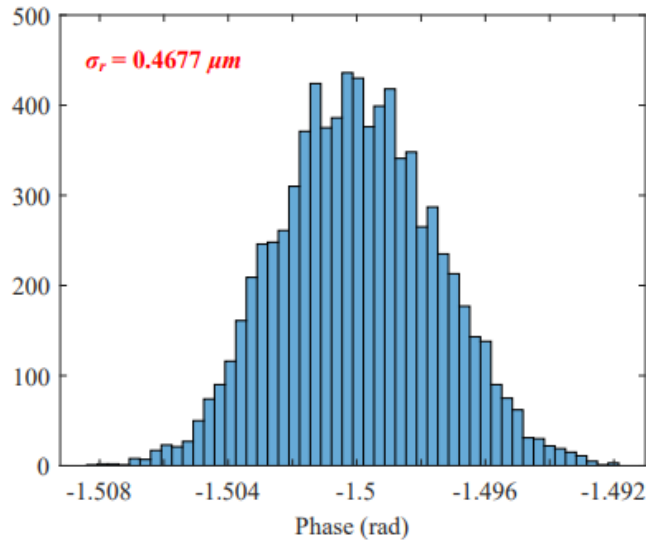
### Safety & Viability

Features extremely **low phase noise** and **transmission power**; completely **biologically safe** for **continuous human monitoring**.

**RF power: 2.594 mW/m<sup>2</sup> ≪ 10 W/m<sup>2</sup> (RF safety program initiation level)**

## Radar Characterization &amp; Optimization (III)

## ■ Sensitivity



- The standard deviation of the phase was calculated by recording the reflection from the laboratory's floor over a continuous period.
- The signal peak (red marker) corresponds to the reflection from a stationary ground surface with a reflection intensity (RCS) comparable to a human thorax.

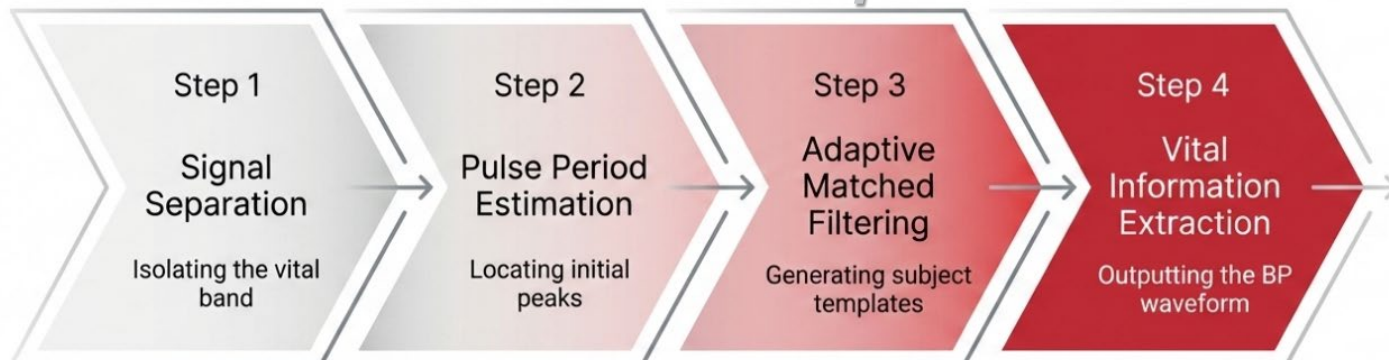
**Phase noise:  $0.4677 \mu\text{m}$  -> High SINR for vital sensing**  
**SNR: 45.12 dB  $\ll$  20 dB required for precise phase tracking**

### Repetitive Waveform Adaptive Matched Filter (RWAMF)

#### Matched Filter

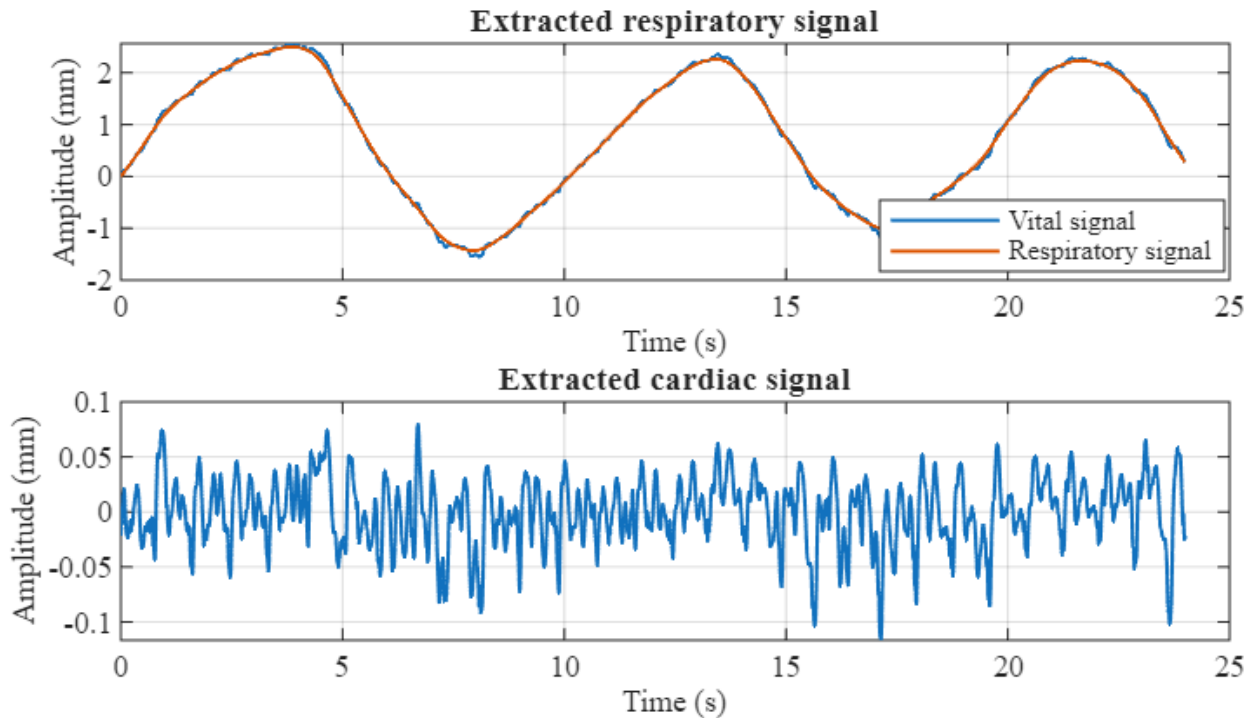
- SINR optimization
- RR & HR estimation
- Cardiac pulse detection and localization
- **Prior knowledge required**  
-> cardiac waveform of each subject

#### Proposed RWAMF



## Signal processing technique (I)

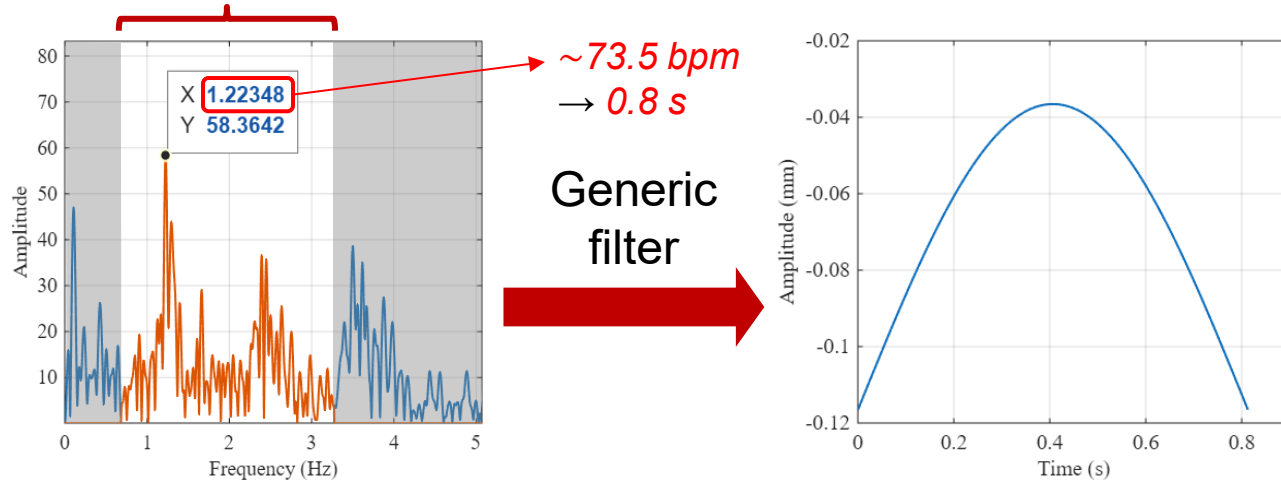
- Extract respiratory signal  $s_r$  with lowpass linear-phase (Finite Impulse Response) FIR filter
- Normal RR of a healthy subject:  $\sim 12$  bpm  $\rightarrow 0.2$  Hz
  - >  $f_s = 333.33$  Hz
  - >  $f_{cutoff} = 0.3$  Hz
  - > order = 300
- Heartbeat signal  $s_h = s_{vital} - s_r$



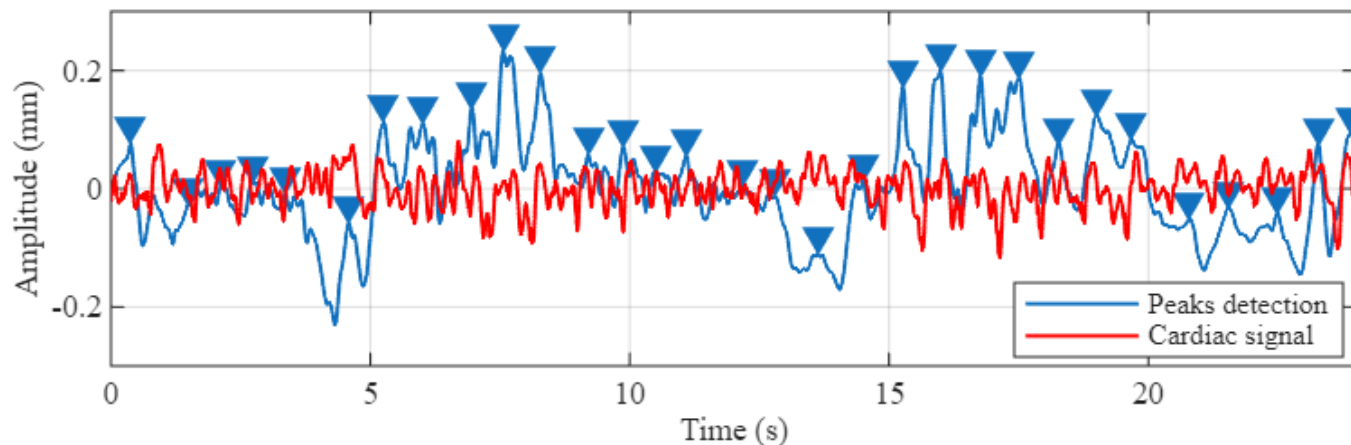
## Signal processing technique (II)

- Cardiac period (HR) estimation based on FFT spectrum

Typical human HR range: 40 to 200 bpm (0.667 Hz to 3.333 Hz)

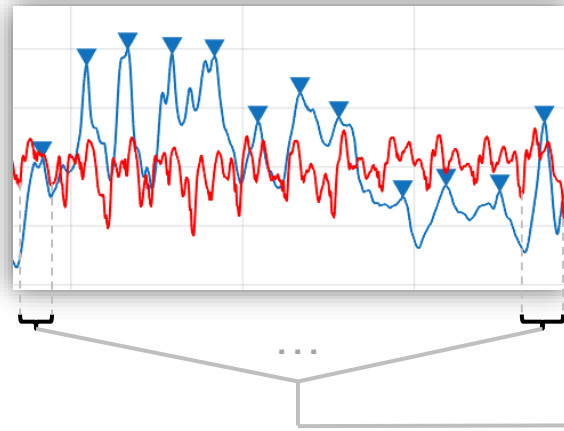


- 1° peaks detection for template signal design

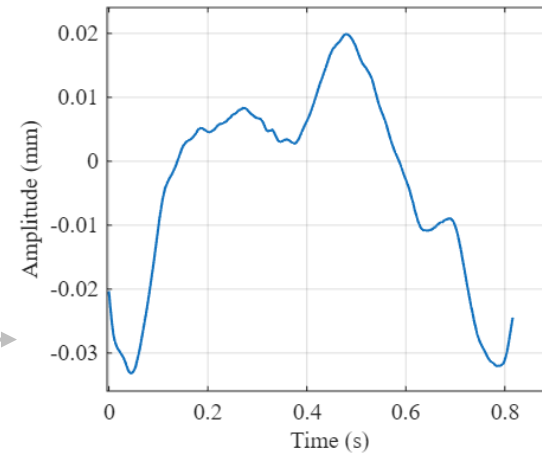


## Signal processing technique (III)

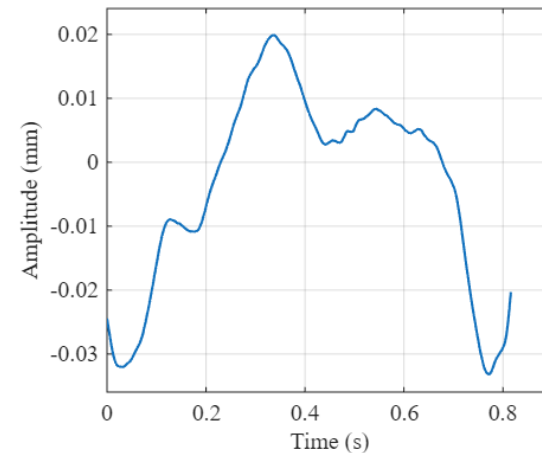
- Template signal & final impulse response for RWAMF



$$\frac{1}{N} \sum_{i=1}^N pulse(i)$$

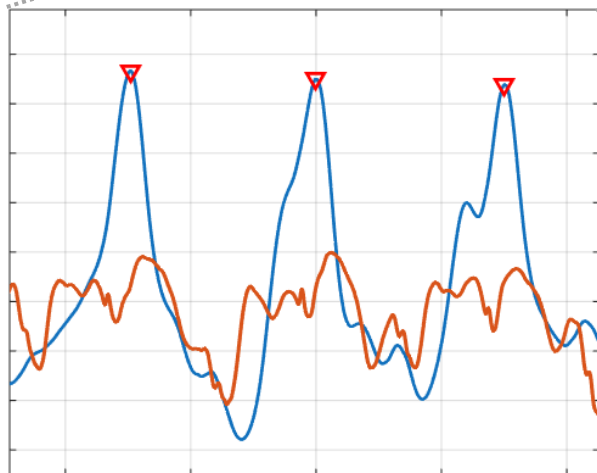
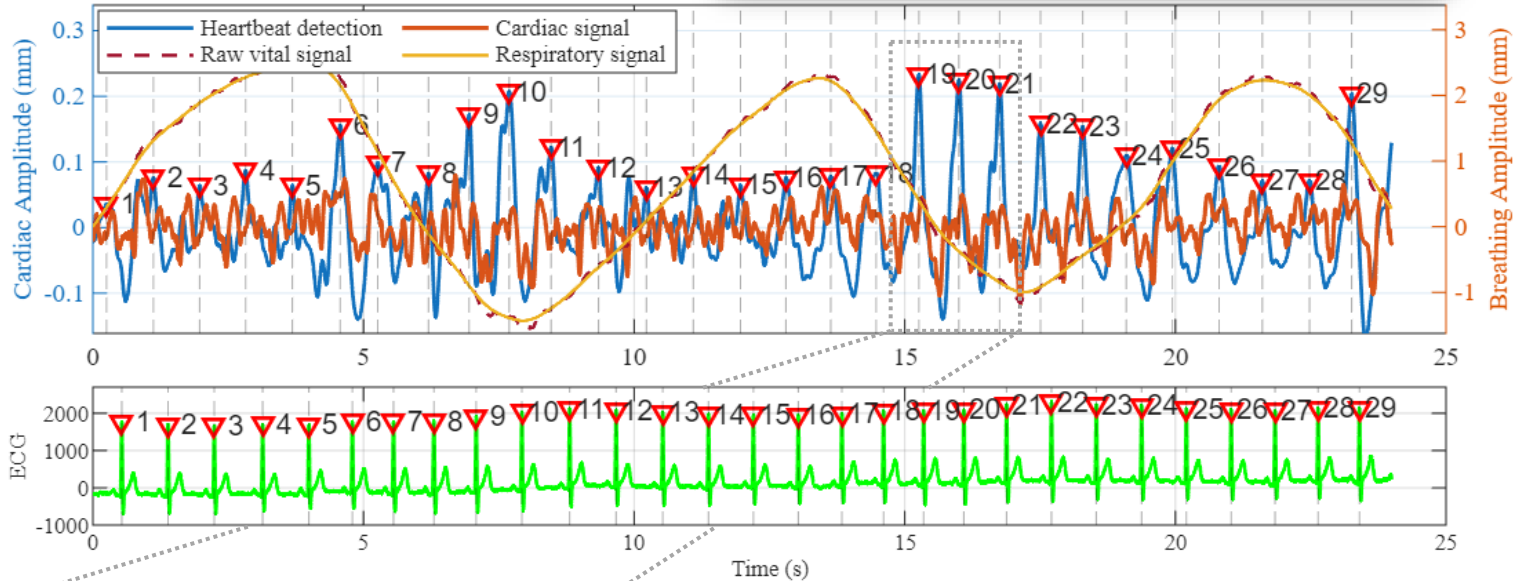


- The template signal is inverted in the time domain and perform 2° filtering on the cardiac signal.



### Final overall result

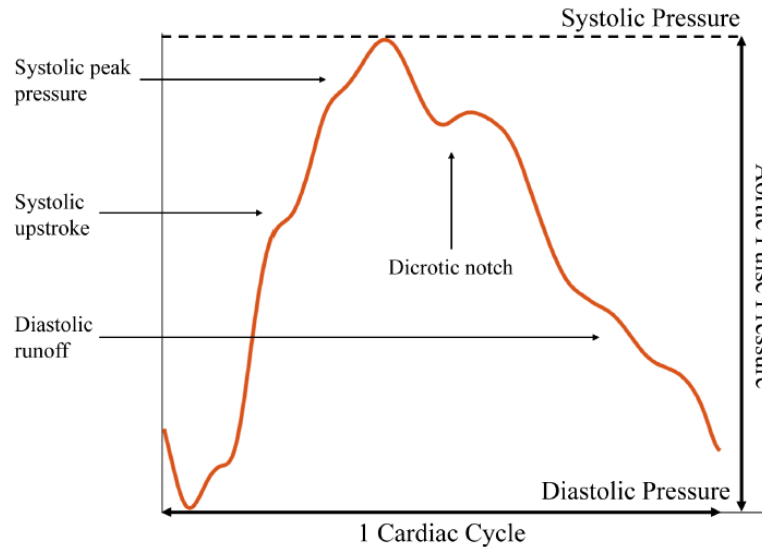
The HR of the subject is: 73.4715 bpm. (by ECG)  
The HR of the subject is: 73.4194 bpm. (by RADAR)



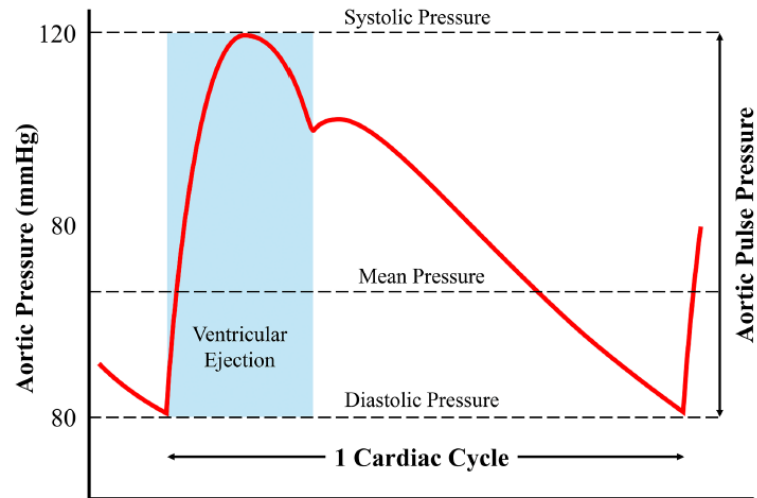
### Output result:

- i) higher amplitude;
- ii) sharp waveform;
- iii) peak is located at the center of the cardiac pulse.

- Blood pressure waveform (BPW) reconstruction



*Average BPW reconstructed from the cardiac signal*



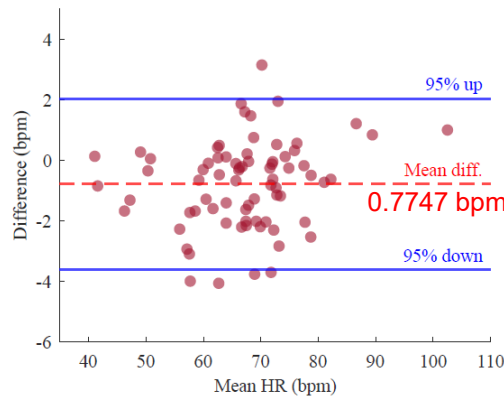
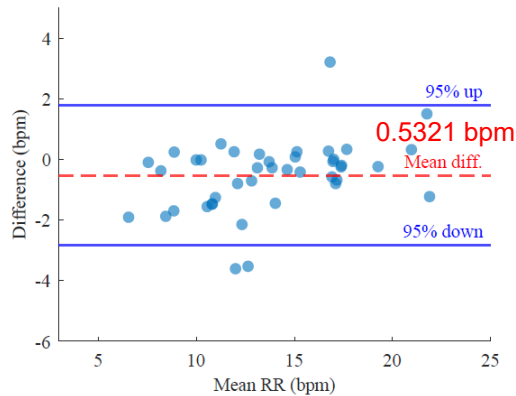
*Typical features of the aortic pulse pressure waveform*

- Each component, such as systolic blood pressure, pulse pressure, diastolic blood pressure, etc., can correspond to the theoretical waveform.

# Contribution 1

## Results (III)

- Evaluation of system and algorithm performance across 16 subjects (different states / positions, 24 s/measur.)
- 10 male and 6 female with an average age of 32.6 years



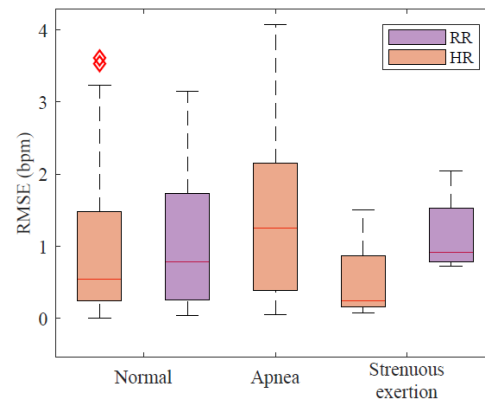
Subject	Gender <sup>1</sup>	Age	Measurement Position	Physiological State	RR (bpm)		HR (bpm)	
					RADAR	Reference	RADAR	Reference
1	M	29	2	Normal	17.00	17.00	81.87	82.50
					16.93	17.00	73.02	72.50
2	M	29	2	Normal	15.08	15.50	66.64	66.85
					NA	NA	62.58	62.50
3	M	30	2	Normal	16.82	17.50	67.71	67.50
					15.08	15.00	62.92	63.00
4	M	62	2	Normal	17.30	17.50	68.22	69.50
					21.27	22.50	71.87	72.00
5	M	28	2	Normal	8.00	8.38	56.77	58.50
					11.51	11.00	60.89	60.90
6	M	30	2	Normal	8.99	8.75	68.57	68.20
					10.23	10.25	66.17	66.42
7	M	30	2	Normal	9.98	10.00	41.13	41.00
					NA	NA	41.15	42.00
8	M	25	2	Normal	17.83	17.50	74.74	74.50
					8.00	9.70	55.66	58.60
9	F	28	2	Apnea-mid	NA	NA	62.99	62.50
					3.39	NA	60.86	62.46
10	M	48	2	Apnea-mid	NA	NA	62.67	62.25
					3.39	NA	60.86	62.46
11	M	25	2	Strenuous exertion	17.25	17.50	103.00	102.00
					2.89	NA	66.38	68.40
12	F	53	2	Normal	16.87	16.00	69.86	71.90
					22.50	NA	73.95	72.00
13	F	27	3	Apnea-mid	22.50	21.00	89.84	89.00
					18.70	17.50	78.56	78.00
14	F	25	4	Strenuous exertion	13.30	14.75	77.42	77.00
					7.19	NA	71.09	73.40
15	F	29	2	Normal	10.19	13.80	59.81	61.10
					16.62	17.20	58.88	59.54
16	F	24	3	Apnea-mid	18.42	15.21	57.72	59.40
					NA	NA	54.72	57.00

### Root Mean Square Error:

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (X_i - Y_i)^2}$$

$X_i$ : bpm by radar;  $Y_i$ : bpm by monitor.

- RR: 1.2804 bpm
- HR: 1.6327 bpm

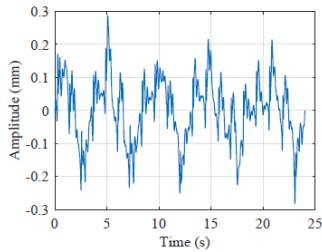
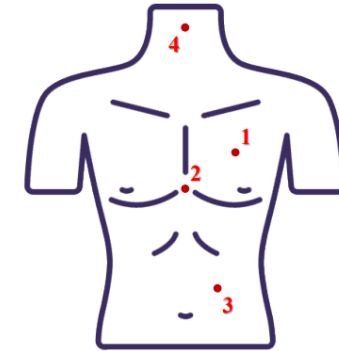


<sup>1</sup>: M: male, F: female.

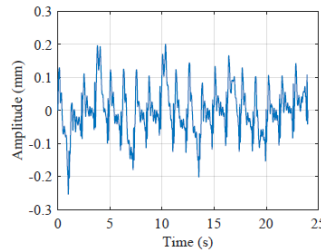
# Contribution 1

## Results (IV)

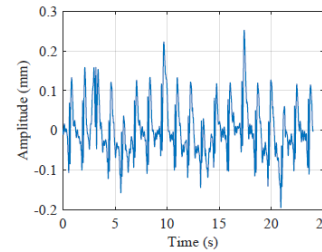
### ■ Measurement position and BPW



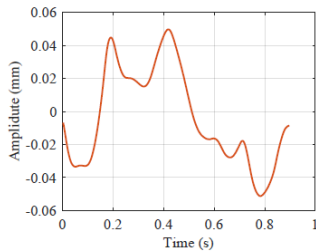
(a)



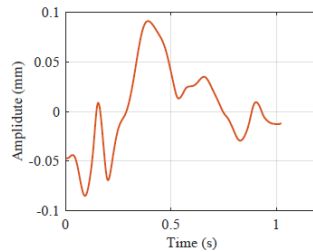
(b)



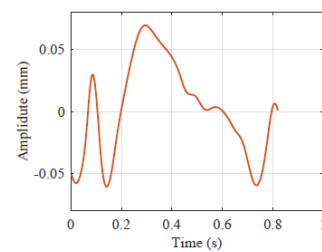
(c)



(d)

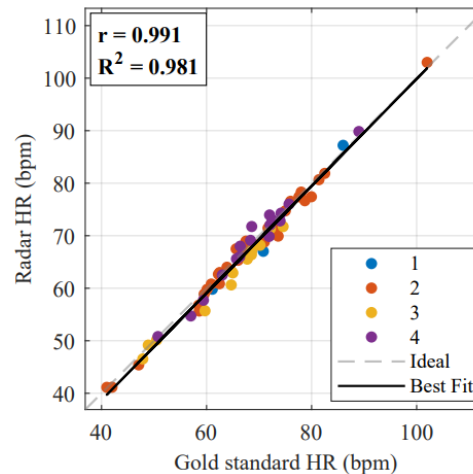
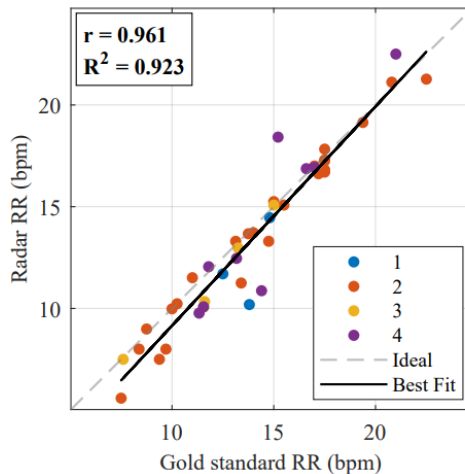


(e)



(f)

- (a) Cardiac waveform of position 1.
- (b) Cardiac waveform of position 2.
- (c) Cardiac waveform of position 3.
- (d) BPW of position 1.
- (e) BPW of position 2.
- (f) BPW of position 3.



- Signal waveform is highly dependent on radar observation position.
- **Pointing problem:** manual alignment is difficult.

# Contribution 2

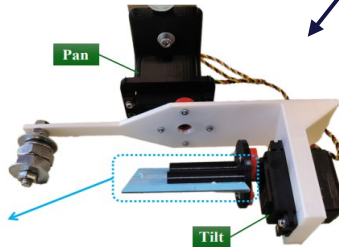
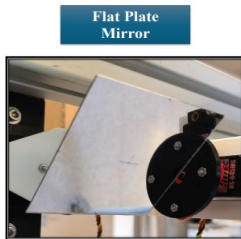
## Enhanced Steering System

### mmVital: Autonomous Radar Beam Orientation

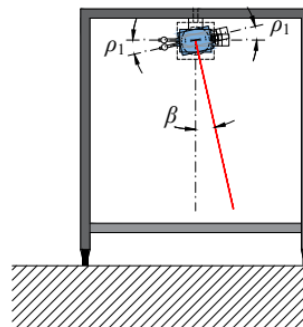
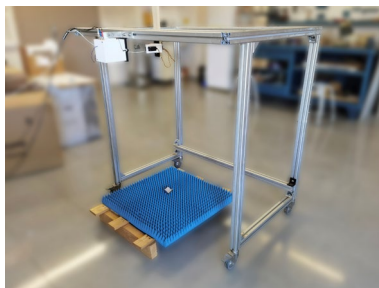
- Problem:** Traditional setups require manual realignment, causing inefficiency



Azimuth ( $\rho_1$ )

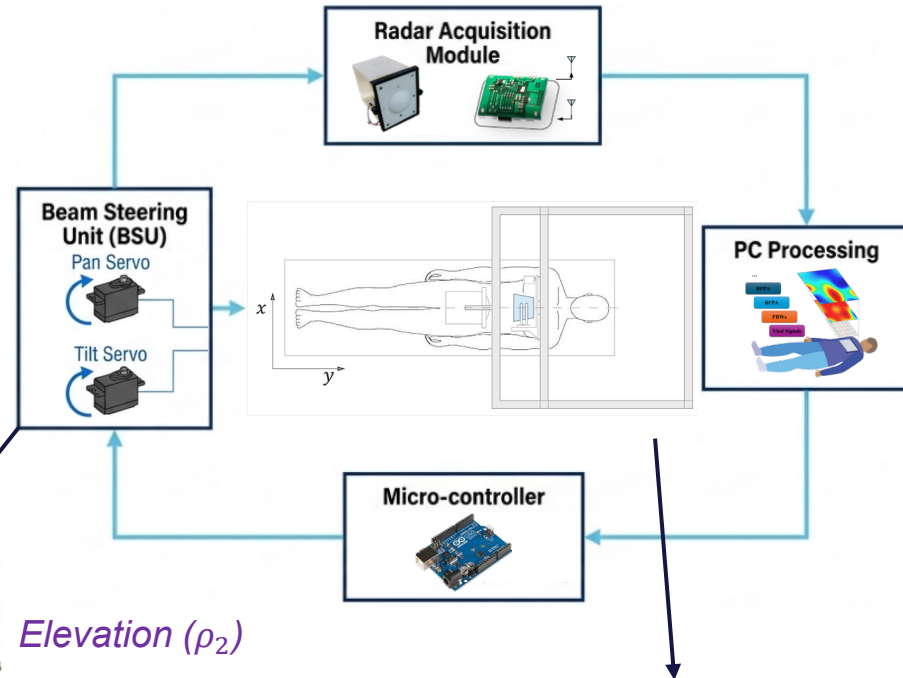
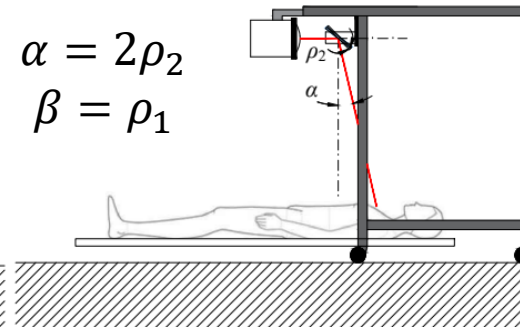


Elevation ( $\rho_2$ )



$$\alpha = 2\rho_2$$

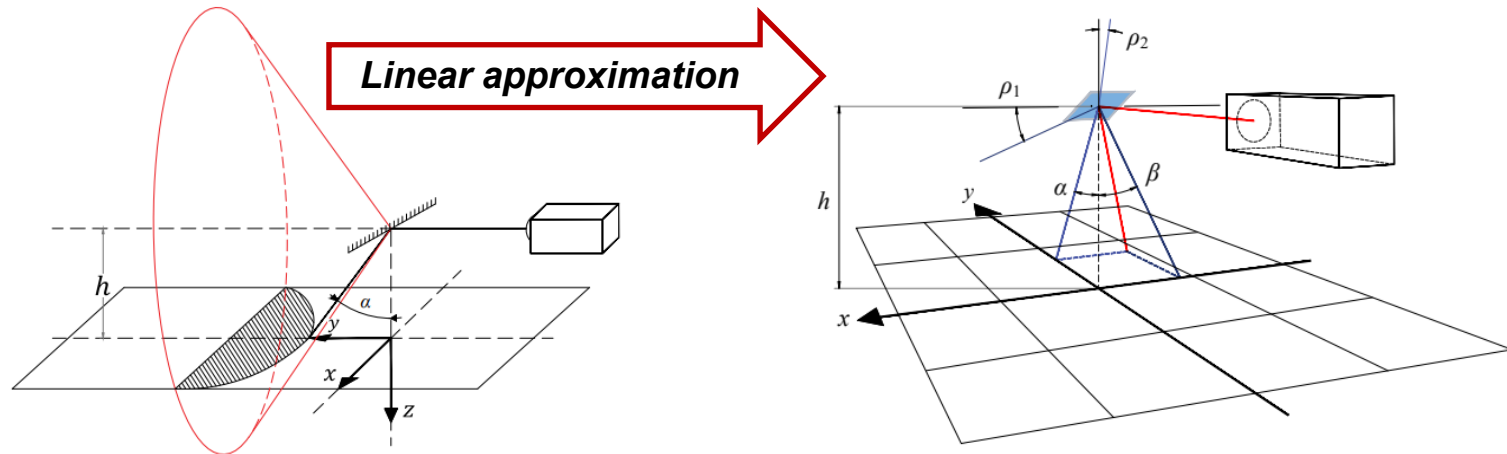
$$\beta = \rho_1$$



# Contribution 2

## Geometric Model

- The sensing region is defined as a Cartesian plane  $(x, y)$  on the body surface at a distance  $h$  from the radar.
- The ideal projection follows a hyperbolic trajectory formed by the intersection of the beam's cone and the measurement plane.



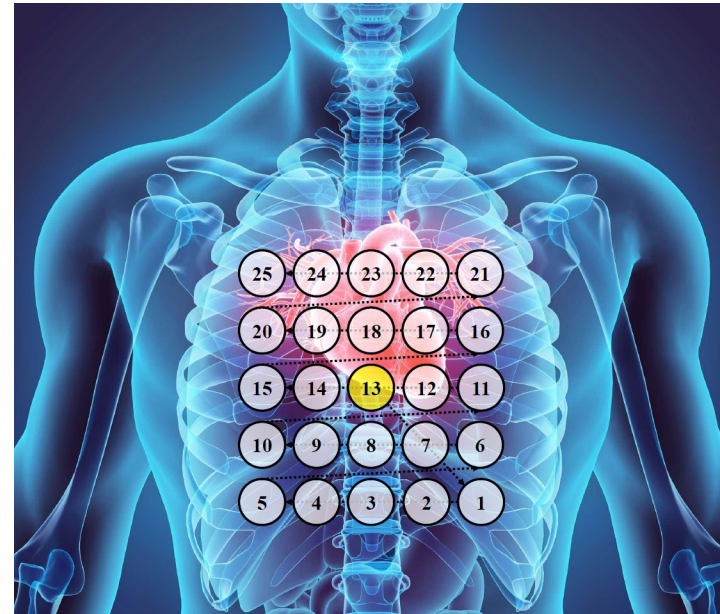
- Mathematical transformation

$$\begin{aligned}
 x &= h \tan \beta \\
 y &= \frac{h}{\cot \alpha \tan \beta}
 \end{aligned}
 \xrightarrow[\text{for } x, y \ll h]{\text{Taylor expansion}}
 \begin{aligned}
 \rho_1 &\approx \frac{x}{h} \\
 \rho_2 &\approx \frac{y}{2h}
 \end{aligned}
 \xrightarrow[\substack{i, j: \text{ variables used} \\ \text{to loop the rows} \\ \text{and columns}}]{\text{step size } \delta}
 \begin{aligned}
 \rho_1 &= \left( j + \frac{N_\beta + 1}{2} \right) \delta \\
 \rho_2 &= \frac{1}{2} \left( i + \frac{N_\alpha + 1}{2} \right) \delta
 \end{aligned}$$

# Contribution 2

## Experimental Configuration

- Matrix dimensions:  
15 cm x 15 cm square area.
- Measurement starting point:  
**Xiphoid appendix** (lower end of the sternum).
- Scanning Protocol:  
Perform a coherent sweep across these 25 discrete positions, capturing vital signals at each node.
- Evaluation: the defined **Jitter Indicator (JI)** quantifies the stability of the detected vital signal by measuring the periodicity of Inter-Beat Intervals (IBI) based on its cardiac signal.



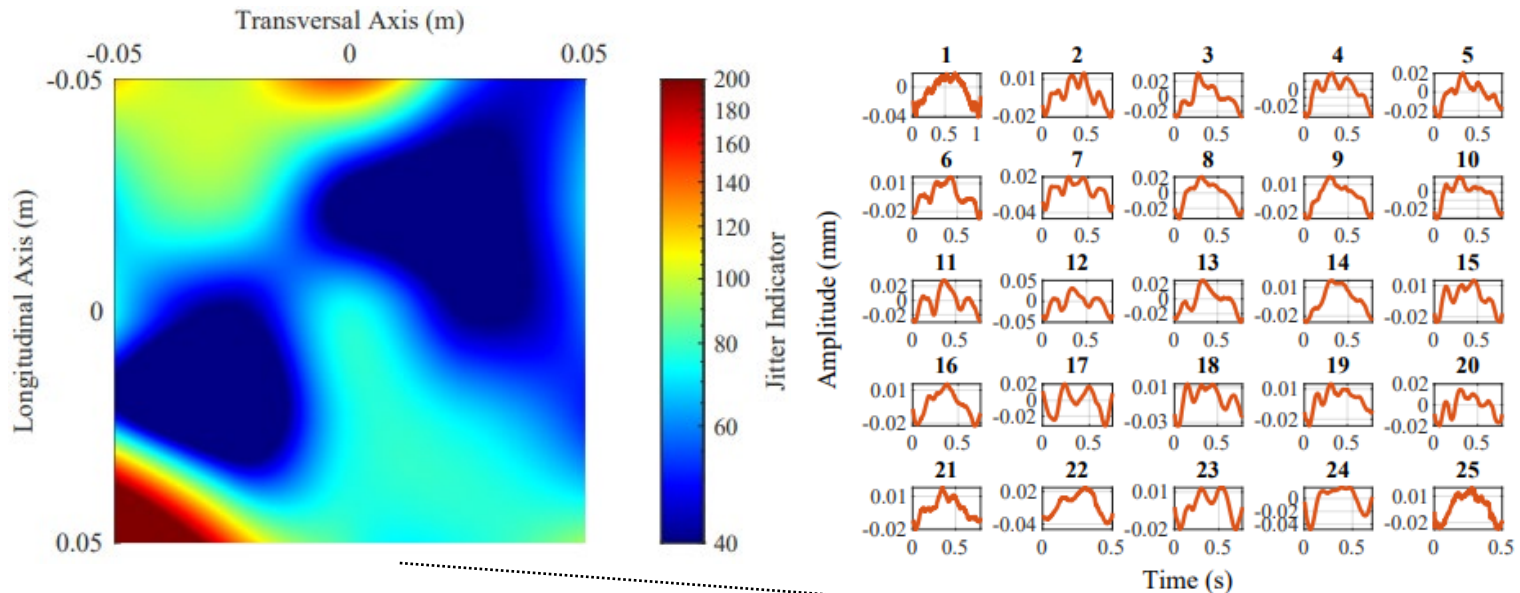
$$JI = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (T_i - \bar{T})^2}$$

*JI*: standard deviation of a vector *T* that represents the IBI between the peaks of the cardiac signal, and *N* is the number of intervals.

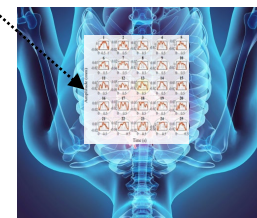
# Contribution 2

## Results (I)

- **Jl map:** features a highly localized, distinct "cold spot" (deep blue) representing the lowest Jl.
- **Cardiac micro-motion waveform (CMW):** can be used to characterize BPW, which conforms to the theoretical changes in arterial pressure waveform during propagation.

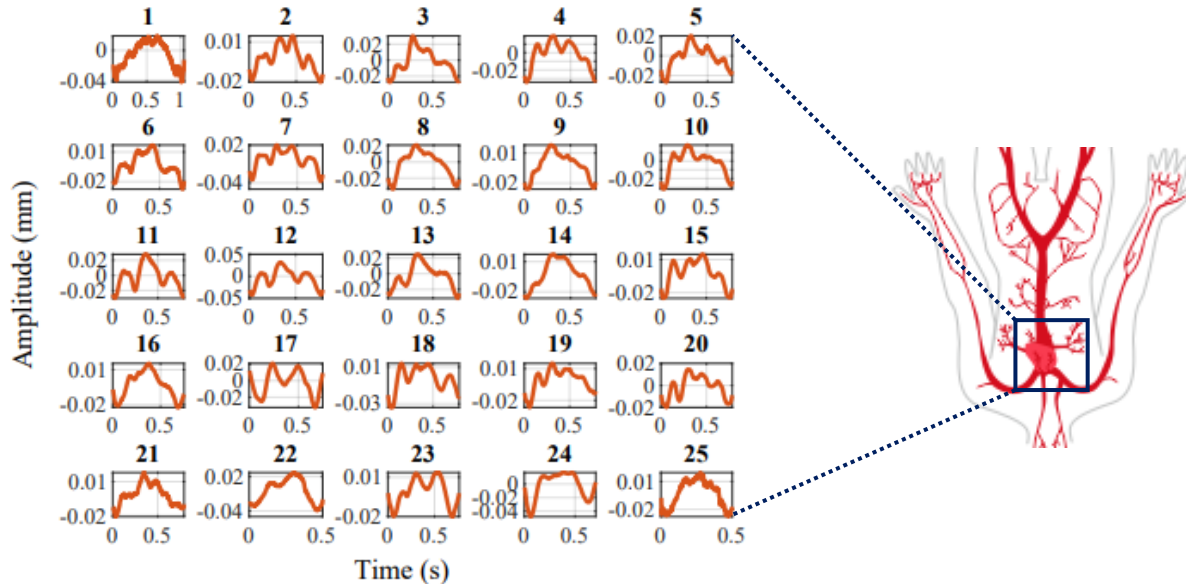


**NOTE:** The measurement results are output in the order of the scanning path, so the distribution of the results at each position in the actual body projection is shown in the figure on the right.

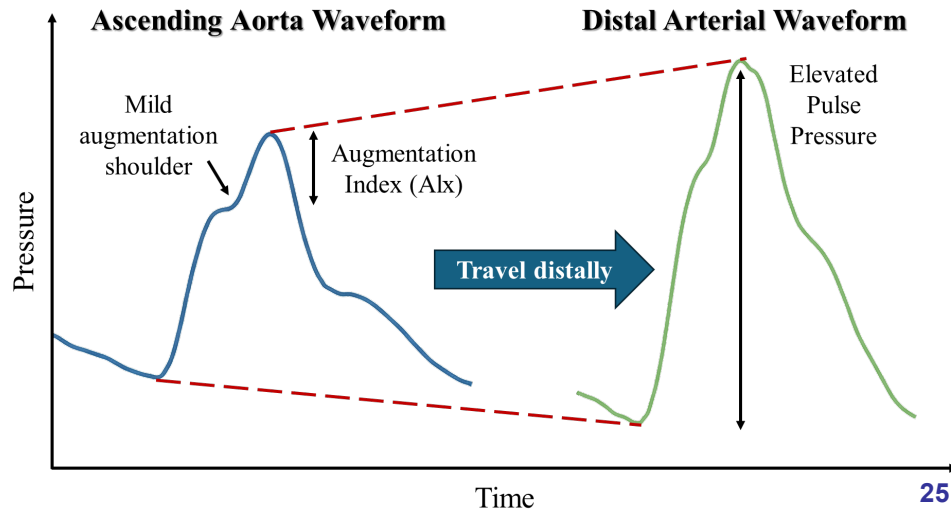


# Contribution 2

## Results (II)



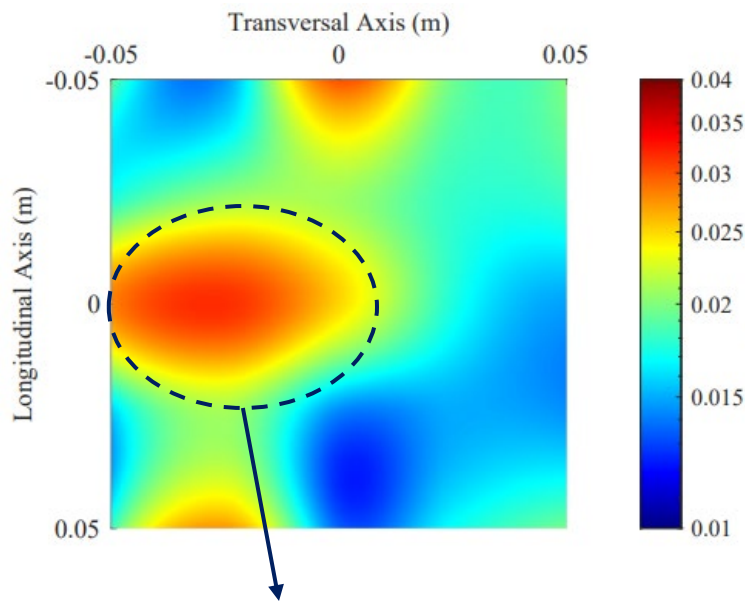
- As the waveform travels distally along the arterial tree, systolic pressure increases and diastolic pressure decreases slightly, resulting in an elevated pulse pressure.



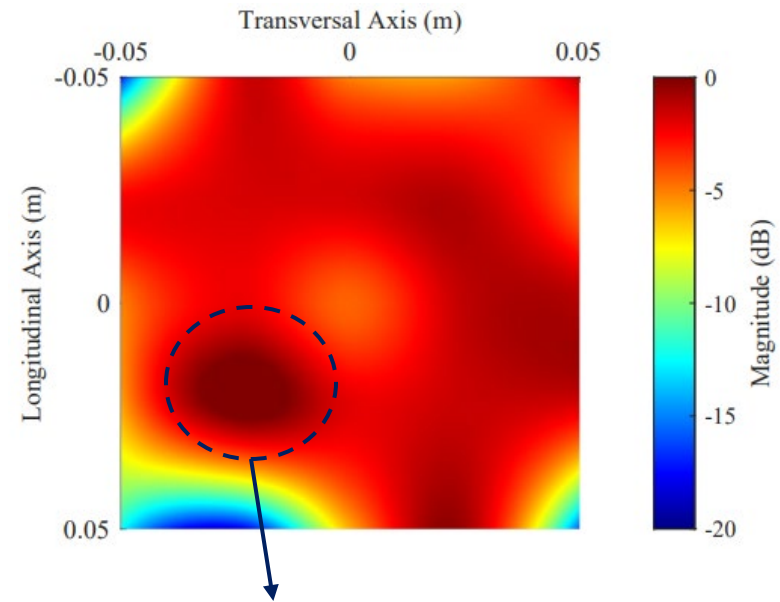
# Contribution 2

## Results (III)

- **Blood Pressure Peak Amplitude (BPPA):** measures the maximum amplitude of chest wall mechanical vibration induced by cardiac activity.
- **Beating Frequency Peak Amplitude (BFPA):** measures the strength of the radar echo signal reflecting off the observed body region.



Corresponds to the lower value area of the JI map.



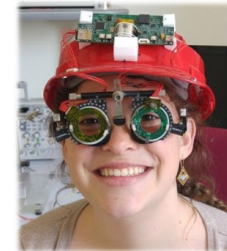
Heart area:  
maximum magnitude

## Eyelid Dynamics Characteristics



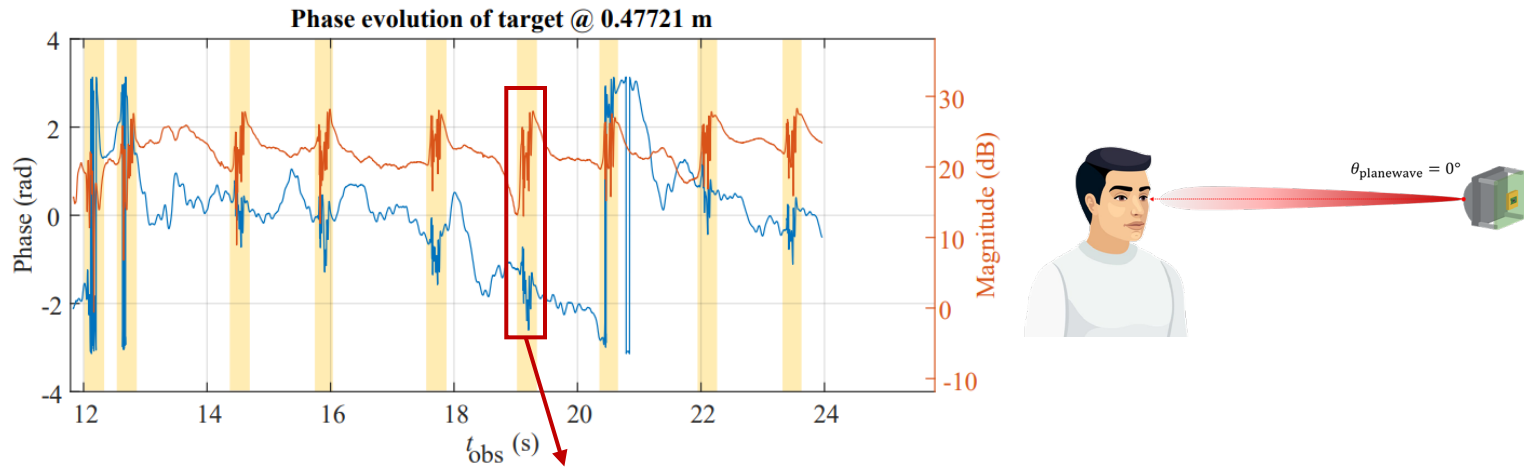
- Radar based eyelid motion monitoring
  - > High sensitivity measurement
  - > Contactless technique
  - > Complex system with cameras (e.g., illumination, privacy...)

- Main application:
    - > fatigue detection (e.g., driver monitoring...)
    - > Diagnosis of neurological disorders
- Collaboration with Hospital  
Sant Joan de Déu Barcelona

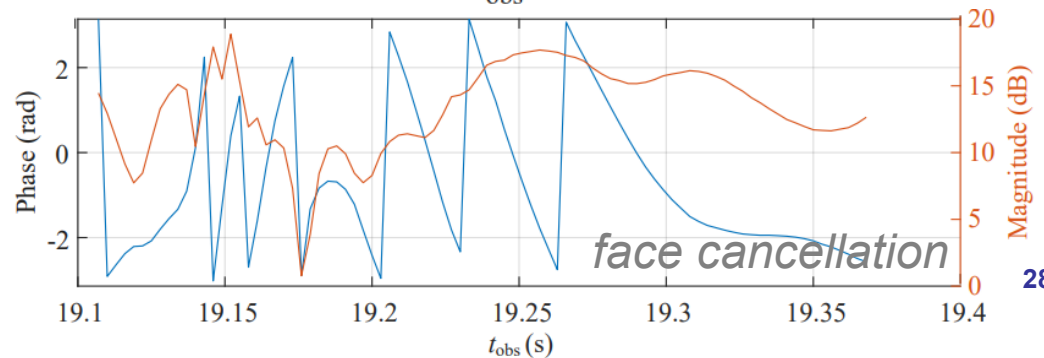
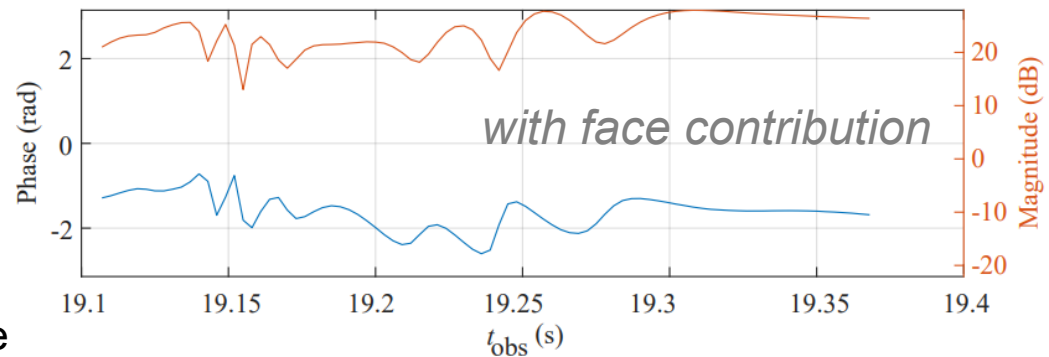


# Contribution 3

## Observation Horizontally

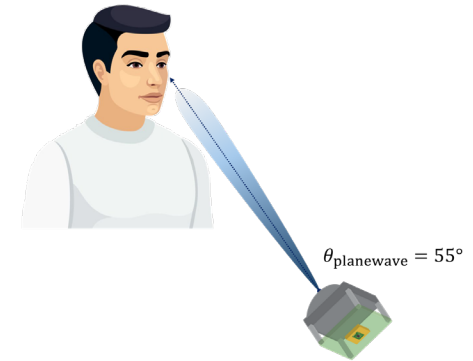
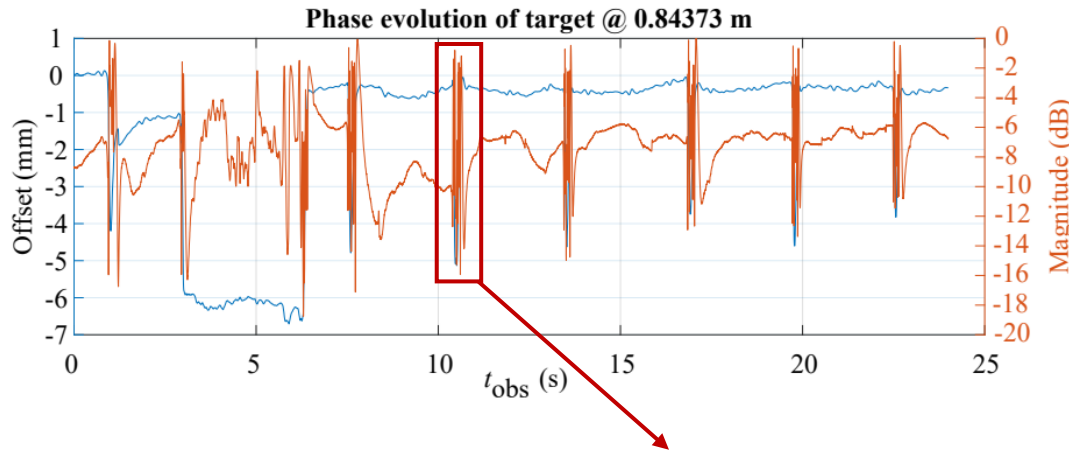


- The background contribution can be estimated by averaging consecutive maxima and minima magnitudes, allowing for the reconstruction of the face phasor.

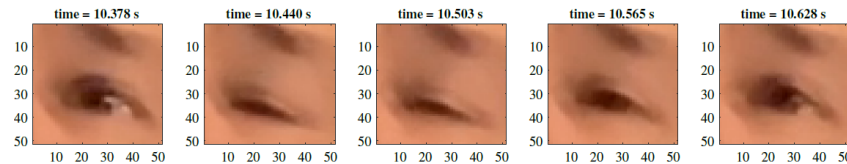
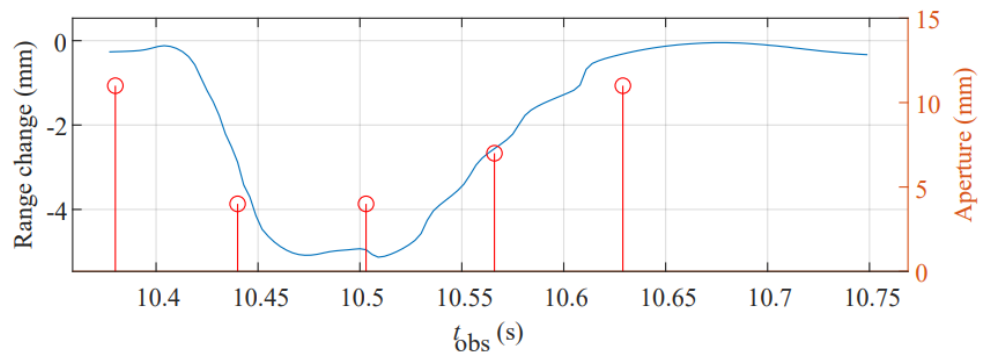


# Contribution 3

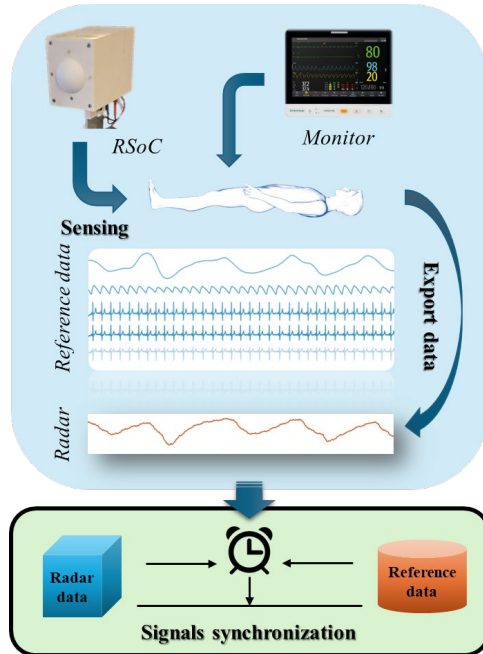
## Slanted Observation



- Blinking movements are detected at approximately  $t = 1, 7.6, 10.5, 13.5, 16.9, 19.7, 22.5$ . The phase evolution clearly reflects the interval of the eyelid voluntary motion, closing and opening at  $t = 2.9$  and  $t = 6.4$ , respectively.



## New Dataset of Radar Vital Signals (I)



### Collaboration:

- Signal Processing and Communications Group (UPC)
- Hospital Universitari Germans Trias i Pujol (HUGTiP)

Ruochen Wu (CommSensLab-UPC, recognized as consolidated research group by the Generalitat de Catalunya GRC-01415, Department of Signal Theory and Communications, Universitat Politècnica de Catalunya, 08034 Barcelona, Spain)

Laura Miro (Signal Processing and Communications Group, Universitat Politècnica de Catalunya, 08034 Barcelona, Spain, recognized as a consolidated research group by the Generalitat de Catalunya through 2021 SGR 01033)

Albert Aguasca (CommSensLab-UPC, recognized as consolidated research group by the Generalitat de Catalunya GRC-01415, Department of Signal Theory and Communications, Universitat Politècnica de Catalunya, 08034 Barcelona, Spain)

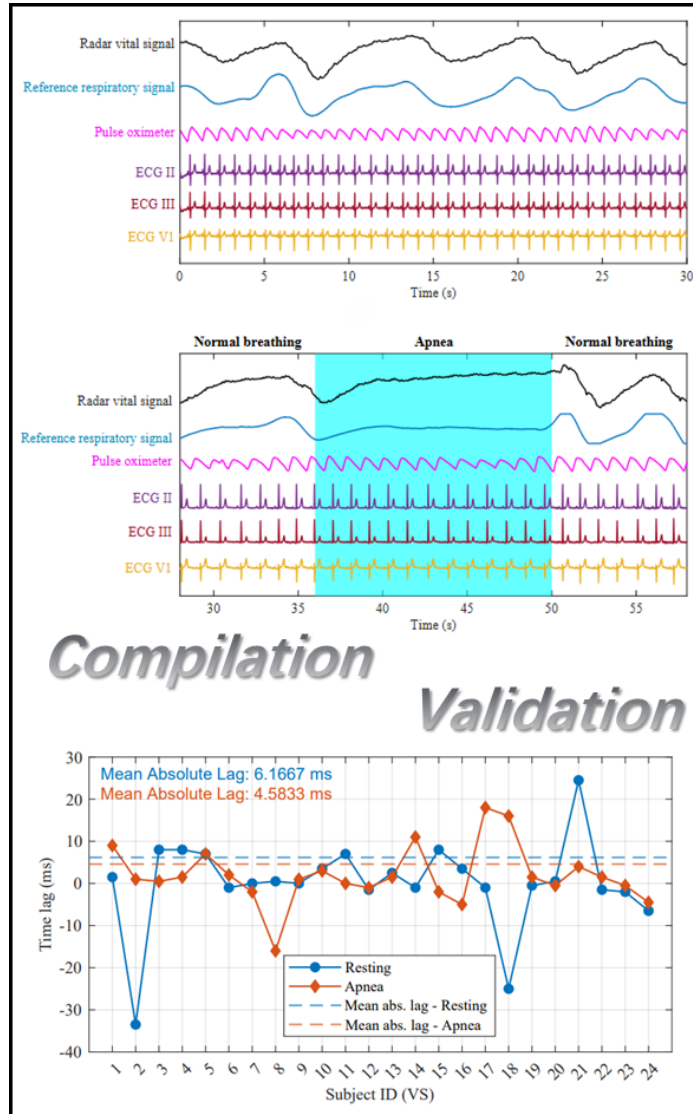
Antoni Broquetas (CommSensLab-UPC, recognized as consolidated research group by the Generalitat de Catalunya GRC-01415, Department of Signal Theory and Communications, Universitat Politècnica de Catalunya, 08034 Barcelona, Spain)

Cosme Garcia (Cardiology Department, Hospital Universitari Germans Trias i Pujol, Badalona 08916, Barcelona, Spain)

Montse Najar (Signal Processing and Communications Group, Universitat Politècnica de Catalunya, 08034 Barcelona, Spain, recognized as a consolidated research group by the Generalitat de Catalunya through 2021 SGR 01033)

The Gap	The Action	The Output
Lack of high-quality, high-frequency (120 GHz) radar vital signal data limits global research.	Partnered with the SPCOM (UPC) and the HUGTiP to record 24 subjects.	An open-access dataset of radar signals synchronized with clinical reference monitors (ECG, PPG, BP, ...).

## New Dataset of Radar Vital Signals (II)



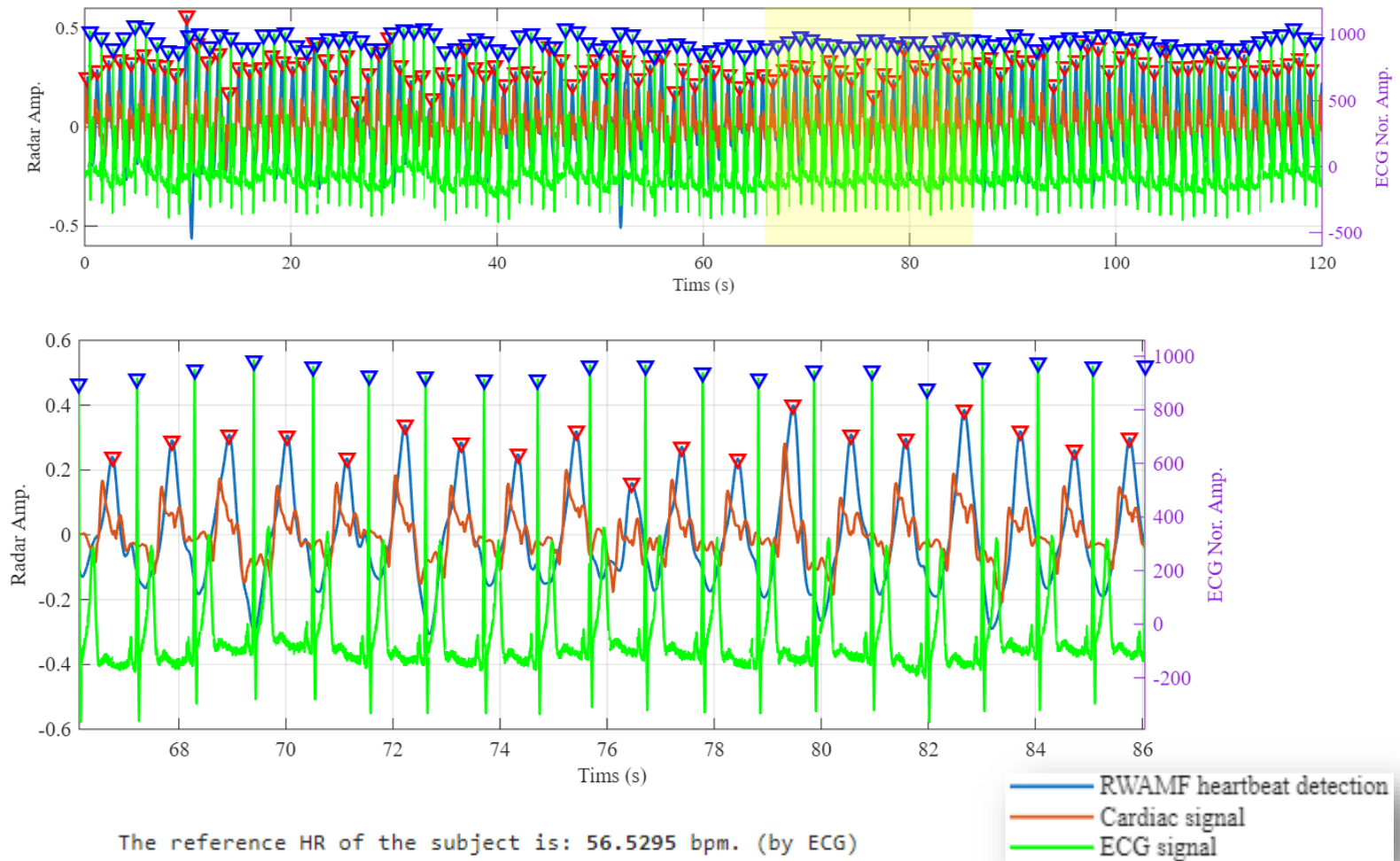
### DATASET AT A GLANCE:

- **Participants:** 24 healthy volunteers
- **Protocol:** 2 minutes normal breathing and breath-holds (apnea) during 2 minutes of normal breathing for each subject
- **Duration:** 5,760 seconds of raw measurements
- **Hardware:** 120 GHz FMCW millimeter-wave RSoC with controlled placement and environment
- **Ethical Review:** approved by the ethics committee of the Universitat Politècnica de Catalunya · BarcelonaTech (*Identification code: 2024-028*)
- **Open Access:**  
<https://doi.org/10.21227/wq68-sv85>



## Algorithm & Dataset Cross-Validation (I)

### Resting

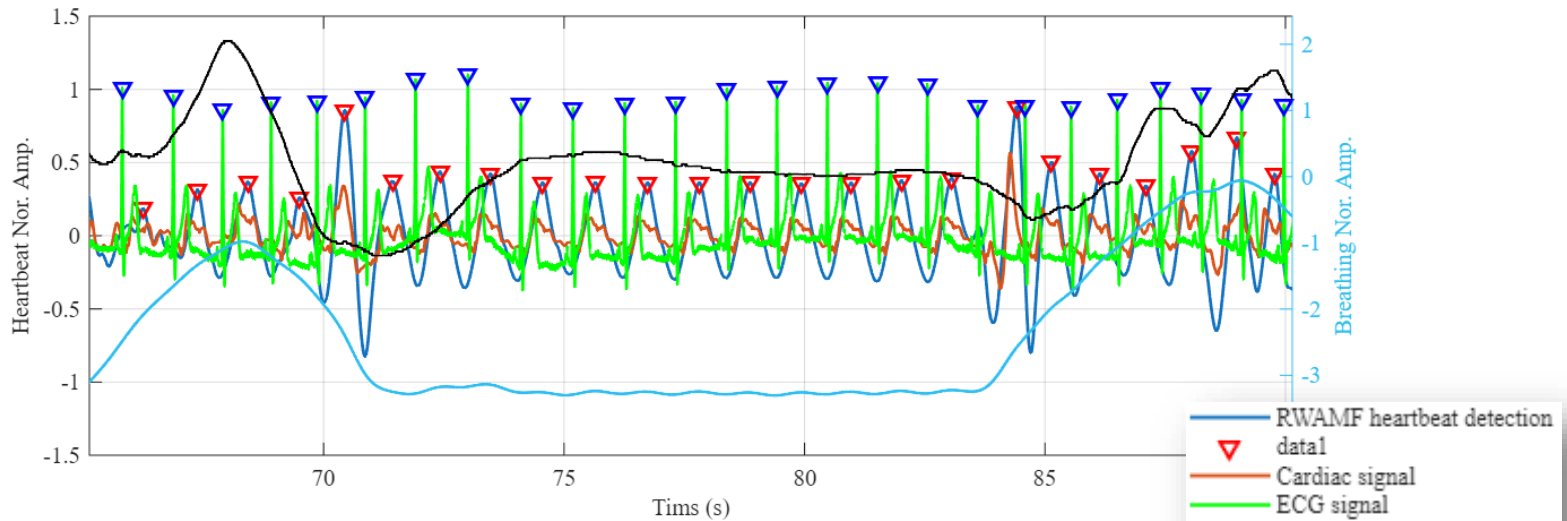
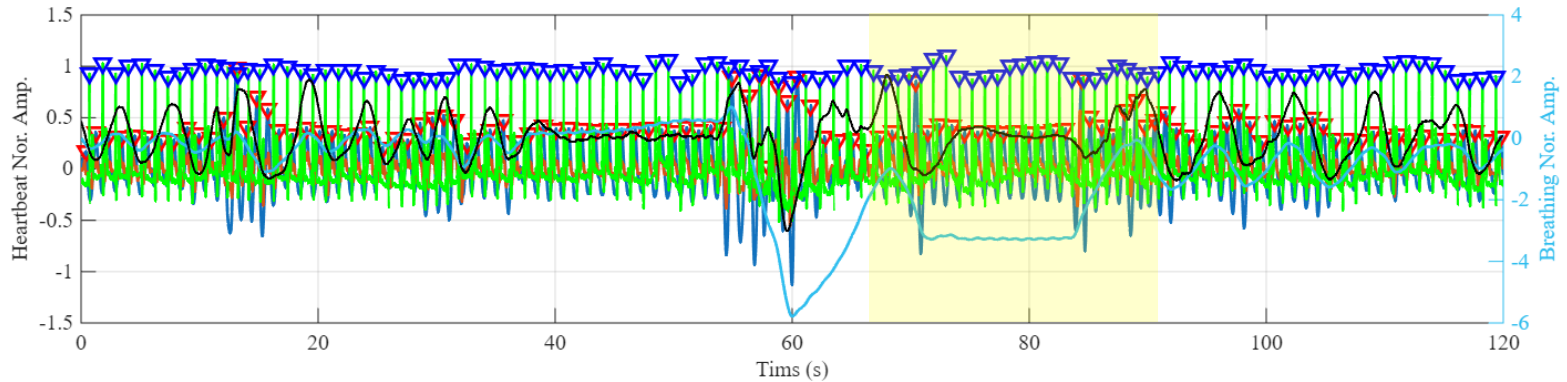


The reference HR of the subject is: 56.5295 bpm. (by ECG)

The HR of the subject is: 56.9329 bpm. (by intervals)

## Algorithm & Dataset Cross-Validation (II)

### ■ Apnea



The reference HR of the subject is: 57.6398 bpm. (by ECG)

The HR of the subject is: 58.1500 bpm. (by intervals)

- RWAMF heartbeat detection
- ▼ data1
- Cardiac signal
- ECG signal
- ▼ data2
- Radar respiratory signal
- Reference respiratory signal

## RADAR-ON-CHIP BASED TECHNIQUES FOR WIRELESS VITAL SENSING AND IoMT

- **mmWave Radar-on-Chip**
  - 120 GHz -> adequate for human micro-movements detection
  - Low cost, compact hardware, narrower beamwidth
- **RWAMF**
  - Robust biometric information
  - Adaptive technique -> without prior knowledge
  - ◆ Next Step: algorithm optimization for real-time processing to satisfy practical requirements.
- **mmVital**
  - Optimal sensing position determination without manual intervention
  - ◆ Limitation: long scan time -> speed optimization
- **Eyelid Dynamics**
  - Eyelid micro-motions detection
  - ◆ Challenges: in-cabin deployment & high-precision pointing
- **Dataset**
  - High quality vital signals of healthy cohort
  - ◆ In progress: patient vital signal dataset via our radar



## Hemodynamics




Blood flow velocity and propagation based on distributed bistatic radar



## Innovative Biometrics

Cardiac signatures analysis for new modality biometric identification and authentication

## Journal Articles

- J1 **Ruochen Wu**, Laura Miro, Albert Aguiasca, Montse Najar, and Antoni Broquetas, “Robust Biometric Information Sensing With mmWave Radar System-on-Chip,” *IEEE Transactions on Mobile Computing*, 2025, ISSN: 1536-1233. doi: [10.1109/TMC.2025.3640267](https://doi.org/10.1109/TMC.2025.3640267). (JCR Q1, IF = 9.2)  **Corresponding to Chapter 3**
- J2 Dominik Patscheider, **Ruochen Wu**, Antoni Broquetas, Albert Aguiasca, and Jordi Romeu, “Eyelid Dynamics Characterization with 120 GHz mmW Radar,” *Sensors*, 2024, ISSN: 1424-8220. doi: [10.3390/s24237464](https://doi.org/10.3390/s24237464). (JCR Q2, IF = 3.5)  **Corresponding to Chapter 5**
- J3 **Ruochen Wu**<sup>†</sup>, Laura Miro<sup>†</sup>, Albert Aguiasca, Antoni Broquetas, Cosme Garcia, and Montse Najar, “A Dataset of 120 GHz Millimeter-Wave Radar Vital Signals With Synchronized Reference Recordings,” *Scientific Data*, 2026, ISSN: 2052-4463. doi: [10.1038/s41597-026-07016-6](https://doi.org/10.1038/s41597-026-07016-6). (JCR Q1, IF = 6.9)  **Corresponding to Chapter 6**
- J4 Laura Miro, **Ruochen Wu**, Albert Aguiasca, Antoni Broquetas, Cosme Garcia, Oriol Estrada, and Montse Najar, “Contactless Acquisition and Decoupling of Respiratory and Cardiac Signals using a 122 GHz FMCW Radar,” *IEEE Journal of Biomedical and Health Informatics*, 2026, ISSN: 2168-2208. doi: [10.1109/JBHI.2026.3673391](https://doi.org/10.1109/JBHI.2026.3673391). (JCR Q1, IF = 6.8)

IEEE TRANSACTIONS ON

## MOBILE COMPUTING




SCIENTIFIC  
DATA

**J-BHI** Journal of Biomedical  
and Health Informatics



## Dataset

IEEE  
DataPort™

- D1 **Ruochen Wu**, Laura Miro, Albert Aguiasca, Antoni Broquetas, Cosme Garcia, and Montse Najar, “A New Dataset for Millimeter-Wave Radar Vital Sensing With Reference Signals,” *IEEE DataPort*, 2025. doi: [10.21227/wq68-sv85](https://doi.org/10.21227/wq68-sv85).  **Corresponding to Chapter 6.**

## Conference Papers

- C1 Laura Miro, **Ruochen Wu**, Antoni Broquetas, Cosme Garcia, and Montse Najar, “Evaluation of Radar-Based Cardiorespiratory Monitoring Under Different Physiological Conditions,” *47th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 2025, ISSN: 2694-0604. doi: [10.1109/EMBC58623.2025.11254838](https://doi.org/10.1109/EMBC58623.2025.11254838).
- C2 Laura Miro, **Ruochen Wu**, Antoni Broquetas, Albert Aguiasca, Oriol Estrada, Cosme Garcia, and Montse Najar, “Extended Kalman Filtering for Radar-Based Cardiorespiratory Tracking,” *48th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 2026, ISSN: 2694-0604.





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# MANY THANKS FOR YOUR ATTENTION!

*¡Muchas gracias! Moltes gràcies!*

**Universitat Politècnica de Catalunya**

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