Th3C-5

# Temporal-Spatial Equivalent Virtual Array Technique for Accurate Vital Sign Monitoring

Yuchen Li#*, Jingyun Lu#*, Shuqin Dong#*, Changzhan Gu#*, Junfa Mao#*

#State Key Laboratory of Radio Frequency Heterogeneous Integration (Shanghai Jiao Tong University), China

*MoE Key Laboratory of Artificial Intelligence, Shanghai Jiao Tong University, Shanghai, China

# Outline



- Introduction
- Principles
- Experiments and results
- Conclusion

# Introduction

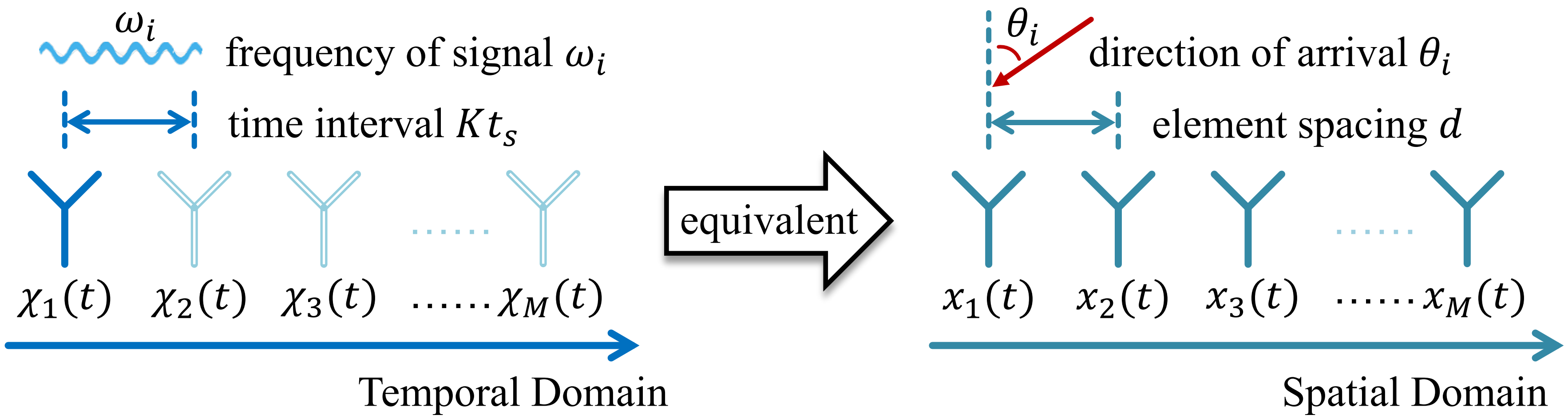


- Non-contact vital signs monitoring has become a hot topic.
- Vital sign detection can be formulated as a spectrum estimation problem.
  - *the spectral leakage and resolution limitation caused by sample data length greatly reduce the accuracy of DFT*
  - *the heartbeat signal can be easily overwhelmed by the third or fourth harmonic of the respiration in frequency spectrum*
- Subspace-based DOA estimation algorithm can be used to achieve the vital sign signal with super-resolution spectral estimation performance

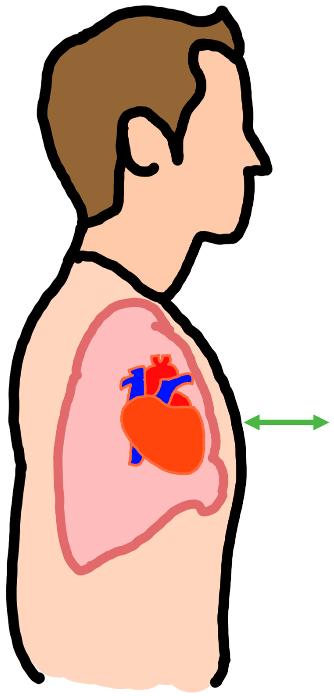
# Principles – Core idea



- The single-channel data of the SISO radar can be decomposed in the temporal domain to form several sub-arrays, which is equivalent to the multi-channel sub-arrays of the SIMO radar in the spatial domain.



# Principles



- **Model of the displacement of the human thorax surface d(t):**

$$d(t) = \sum_{i=1}^{P} A_i \cdot \exp[\, j(\omega_i t + \varphi_i)]$$

- where $P$ is the number of all frequency components, $A_i/\omega_i/\varphi_i$ are the amplitude, angular frequency and the initial phase of the i-th frequency component, respectively.

# Principles

- **IF signal recombined from I/Q channels of CW radar:**

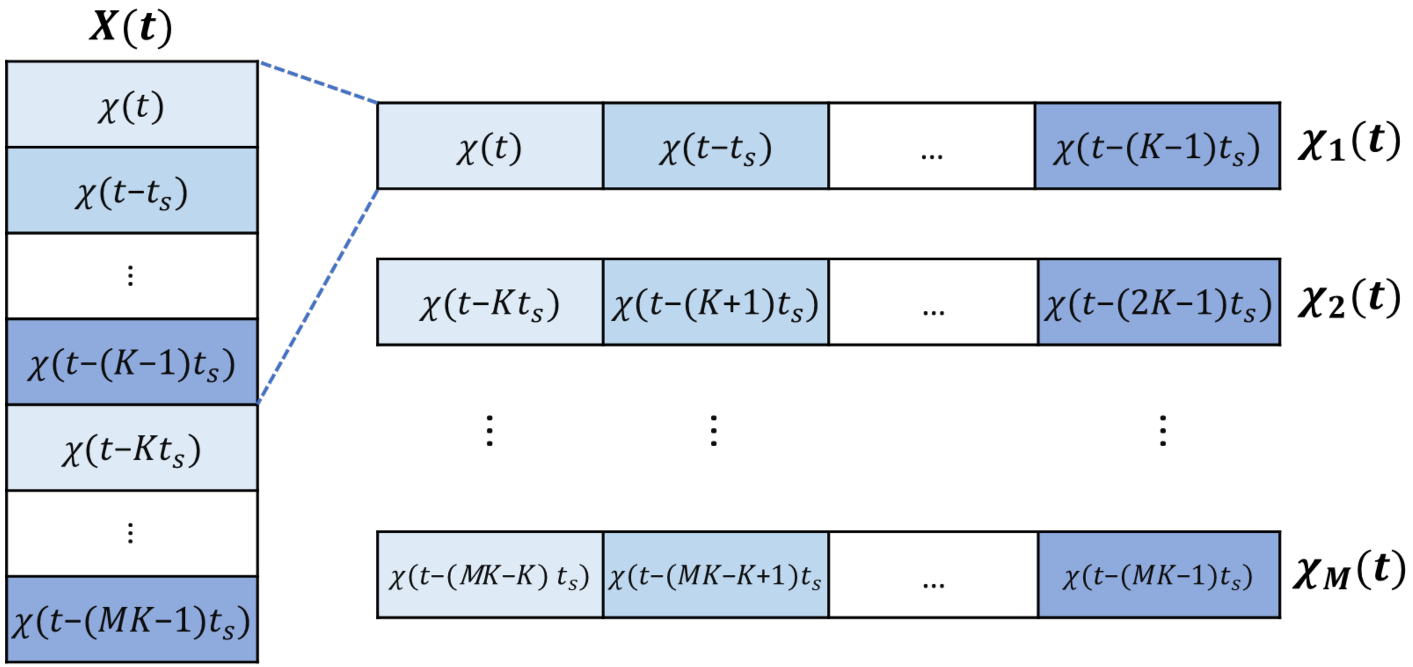
$$X_{IF}(t) = A_{IF} \cdot \exp\left[j\left(\frac{4\pi}{\lambda}(d_0 + d(t)) + \Delta\theta(t)\right)\right]$$

- where $A_{IF}$ is the amplitude of the signal, $\lambda$ is the wavelength, $d_0$ is the initial distance between human and radar, $d(t)$ is the displacement of the thorax surface and $\Delta\theta(t)$ is the residual phase.

# Principles



- **Single channel data segmentation of CW radar:** $\boldsymbol{\chi_i(t) = \Phi(t-(i-1)Kt_s)}$
- The single-channel data is divided into $M$ segments, which are equivalent to $M$ receiving array elements. The phase delay between two adjacent array element is $Kt_s$.



# Principles



- The received data of the whole virtual array can be organized as:

$$\boldsymbol{\chi}(t)=\begin{bmatrix}\chi_1(t)\\ \chi_2(t)\\ \cdots\\ \chi_M(t)\end{bmatrix}=A(\omega)S(t)+N(t)$$

$$=\begin{bmatrix}1 & 1 & \cdots & 1\\ e^{j\omega_1 Kt_s} & e^{j\omega_2 Kt_s} & \cdots & e^{j\omega_P Kt_s}\\ \cdots & \cdots & \cdots & \cdots\\ e^{j(M-1)\omega_1 Kt_s} & e^{j(M-1)\omega_2 Kt_s} & \cdots & e^{j(M-1)\omega_P Kt_s}\end{bmatrix}\times\begin{bmatrix}A_1 e^{j(\omega_1 t+\varphi_1)}\\ A_2 e^{j(\omega_2 t+\varphi_2)}\\ \cdots\\ A_P e^{j(\omega_P t+\varphi_P)}\end{bmatrix}+\begin{bmatrix}n(t)\\ n(t-Kt_s)\\ \cdots\\ n(t-(M-1)Kt_s)\end{bmatrix}$$

- where $A(\omega)=[a(\omega_1),a(\omega_2),\dots,a(\omega_P)]$ stands for the array manifold vector, $a(\omega_i)=\left[1,e^{j\omega_i Kt_s},\dots,e^{j(M-1)\omega_i Kt_s}\right]^T$ is the steering vector of $\omega_i$, $S(t)=[s_1(t),s_2(t),\dots,s_P(t)]^T$ is the signal vector, and $s_i(t)=A_i e^{j(\omega_i t+\varphi_i)}$ is the signal of the *i-th* frequency component.

# Principles

- The influence of a movement with a frequency $\omega_i$ on a single-channel received signal is equivalent to the influence of an incoming wave with an DOA angle $\theta_i$ incident on $M$ receiving array elements.

$$e^{j(\omega_i K t_s)} = e^{j(\frac{2\pi d}{\lambda}\sin\theta_i)}$$

$$\theta_i = \sin\left(2K\frac{f_i}{f_s}\right)^{-1}$$

(assume $d = \lambda/2$)

- To avoid ambiguity when solving angles: $\omega_i K t_s \leq \pi$
  - $\mathrm{K} \leq f_s/2f_i$
- Consider that the sin function is most sensitive at 0° :
  - The value of K should be as large as possible
- $K = \lfloor f_s/2f_i \rfloor$ ($\lfloor\cdot\rfloor$ denote flooring function)

# Principles

- Principle of equivalence:
  - The number of equivalent linear array elements $M$ :
    - $M = \frac{T_{OI}}{Kt_s}$

$T_{OI}$ is the duration of the observation interval
$t_s$ is the sampling interval

  - The angle of equivalent incident signal $\theta_i$ :
    - $\theta_i = \sin\left(2K\frac{f_i}{f_s}\right)^{-1}$

$K$ is the number of snapshots for each equivalent virtual array

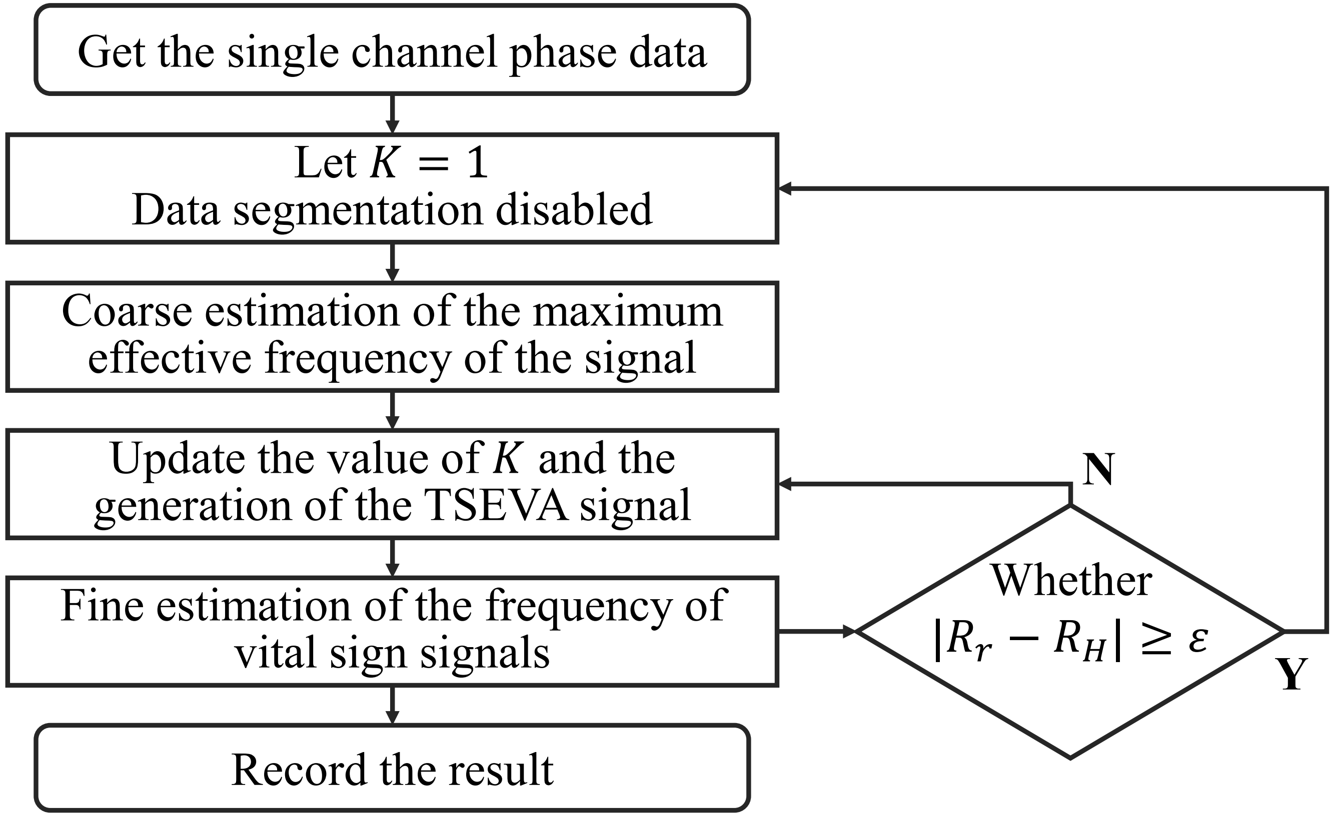
  - The optimal choice of parameter $K$ :
    - $K = \lfloor f_s/2f_i \rfloor$

$f_s$ is the sampling frequency
$f_i$ is the frequency of the $i^{th}$ motion

# Principles



- A coarse-to-fine estimation method is for respiration rate and heart rate monitoring based on the proposed TSEVA theory:

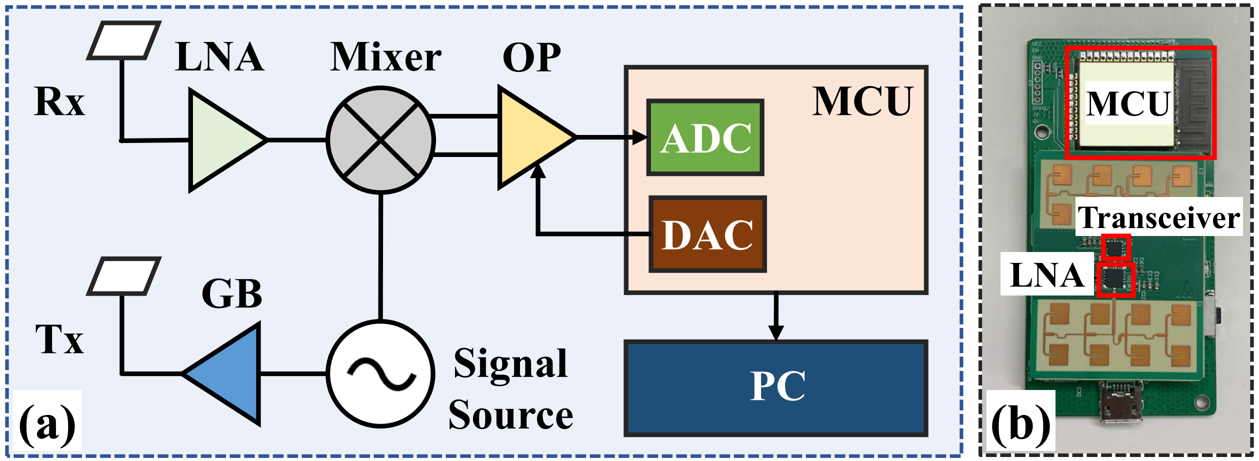



Flow chart of the TSEVA-based vital sign monitoring method

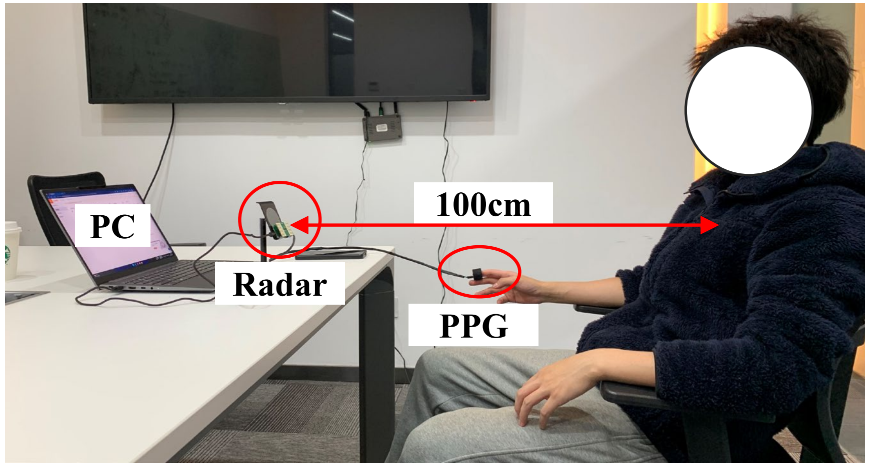
# Experiments and results



- Radar hardware and experimental setup:



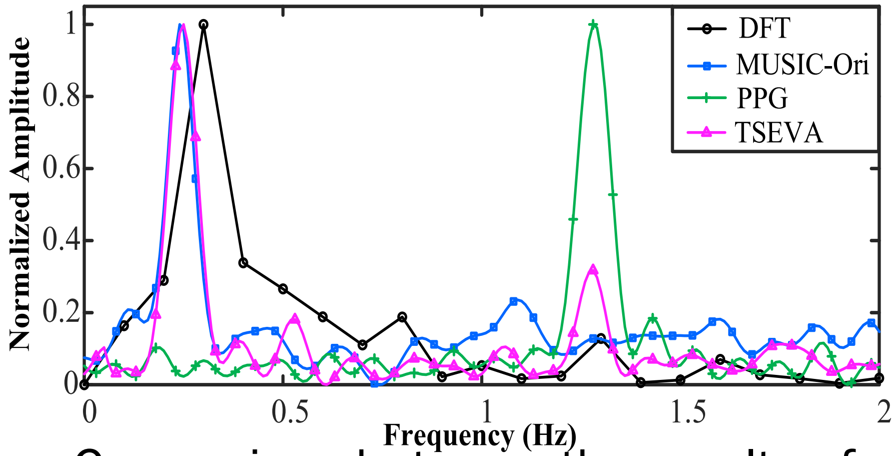

Block diagram (a) and the photo (b) of the SIMO CW radar system



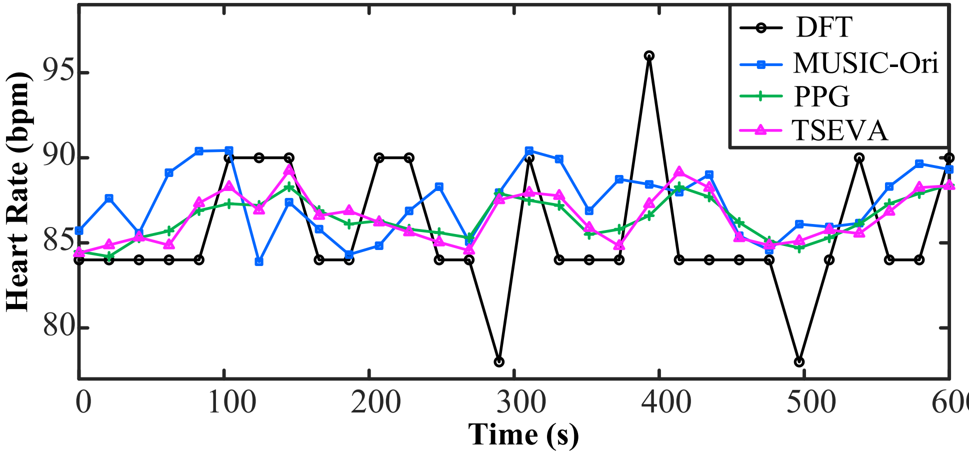

Photograph of the experimental setup

# Experiments and results

- The result obtained by the proposed TSEVA-based method is 0.253Hz for respiration and 1.261Hz for heartbeat, which is the same as the result of PPG.
- The proposed TSEVA-based method performed best, with high accuracy and high stability over the entire time period, and RMSE=0.875.




Comparison between the results of different methods and ground truth




Heart rate estimation results over a 10-minute data

$T_{OI} = 10\text{s}$ and $f_s = 100\text{Hz}$

# Conclusion – Advantage

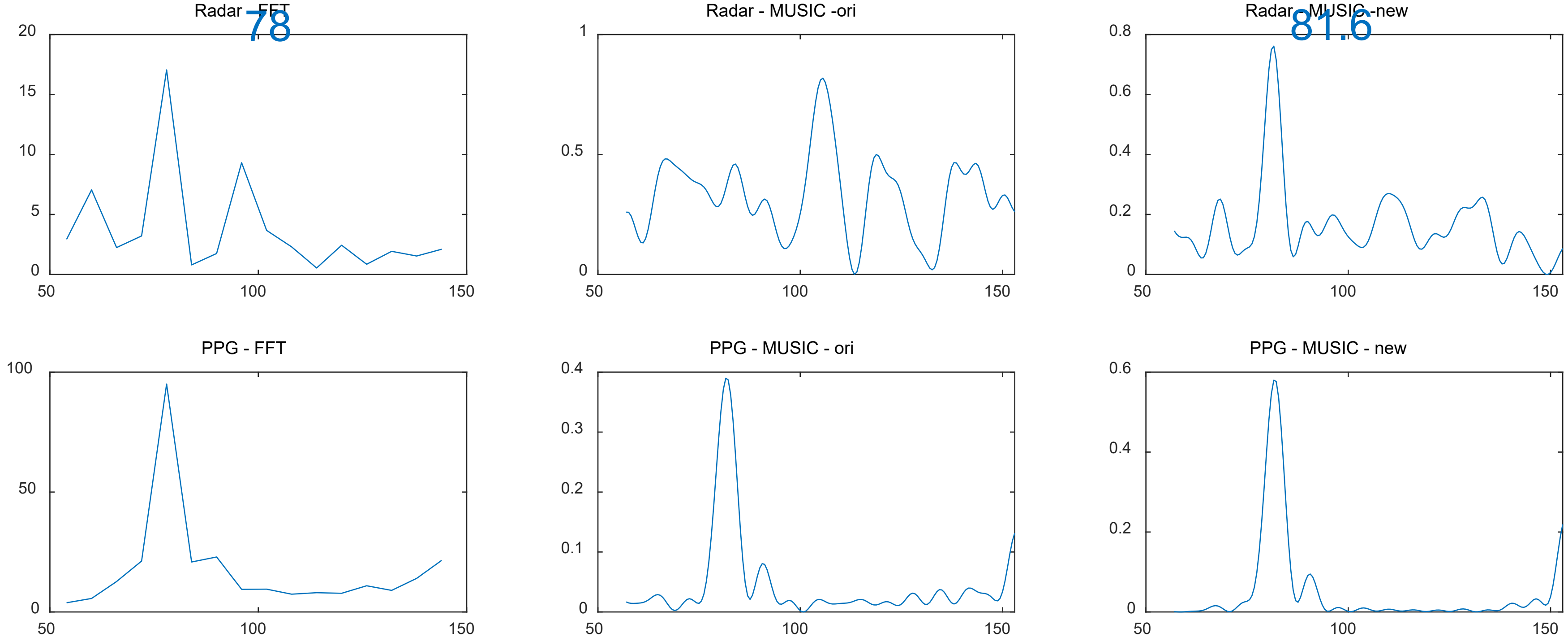
1. Can acquire movement frequency with super-resolution in shorter $T_{OI}$:

Raw FFT Radar: 78

Ori-MUSIC Radar: 105

New-MUSIC Radar: 81.6

$T_{OI}$ = 10s
FFT resolution 6bpm




Increased accuracy by about 5%

# Conclusion – Advantage



2. All DOA methods can be equally applied to the frequency localization of the target signal.

3. Since every frequency component of motion can be acquired with super-resolution, the relationship between respiratory harmonics and heartbeat can be finely distinguished.

# Conclusion – Risk

- High SNR required (prefer FMCW phase information)
- Well balanced I&Q signal required