ECE 598HH: Advanced Wireless Networks and Sensing Systems

Lecture 13: Wireless Sensing Part 2
Haitham Hassanieh

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

CSL: COORDINATED SCIENCE LAB

*Slides Courtesy of Fadel Adib

Interest in Sensing the Human Body

Heart Rate

Breathing

Locations

Gestures

Heart Rate

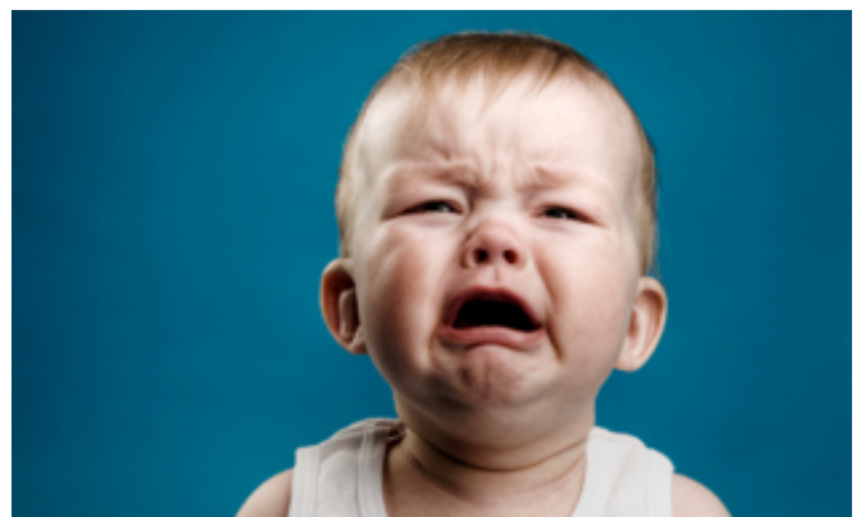
Breathing

Locations

Gestures

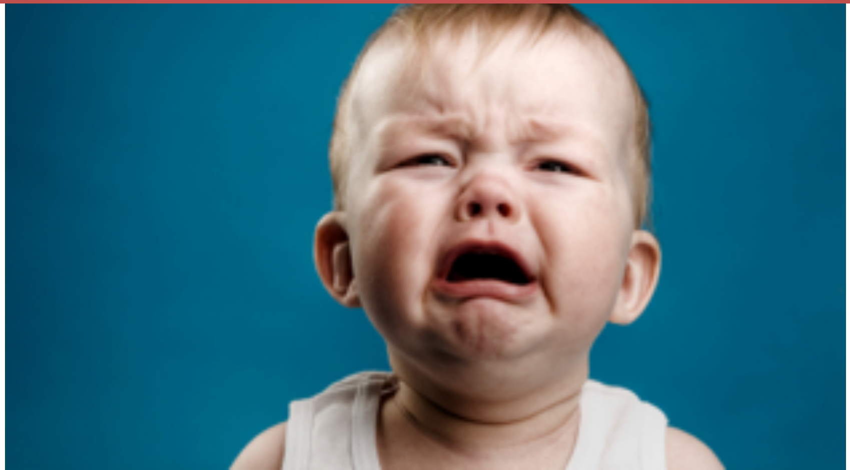
On-body sensors can be cumbersome

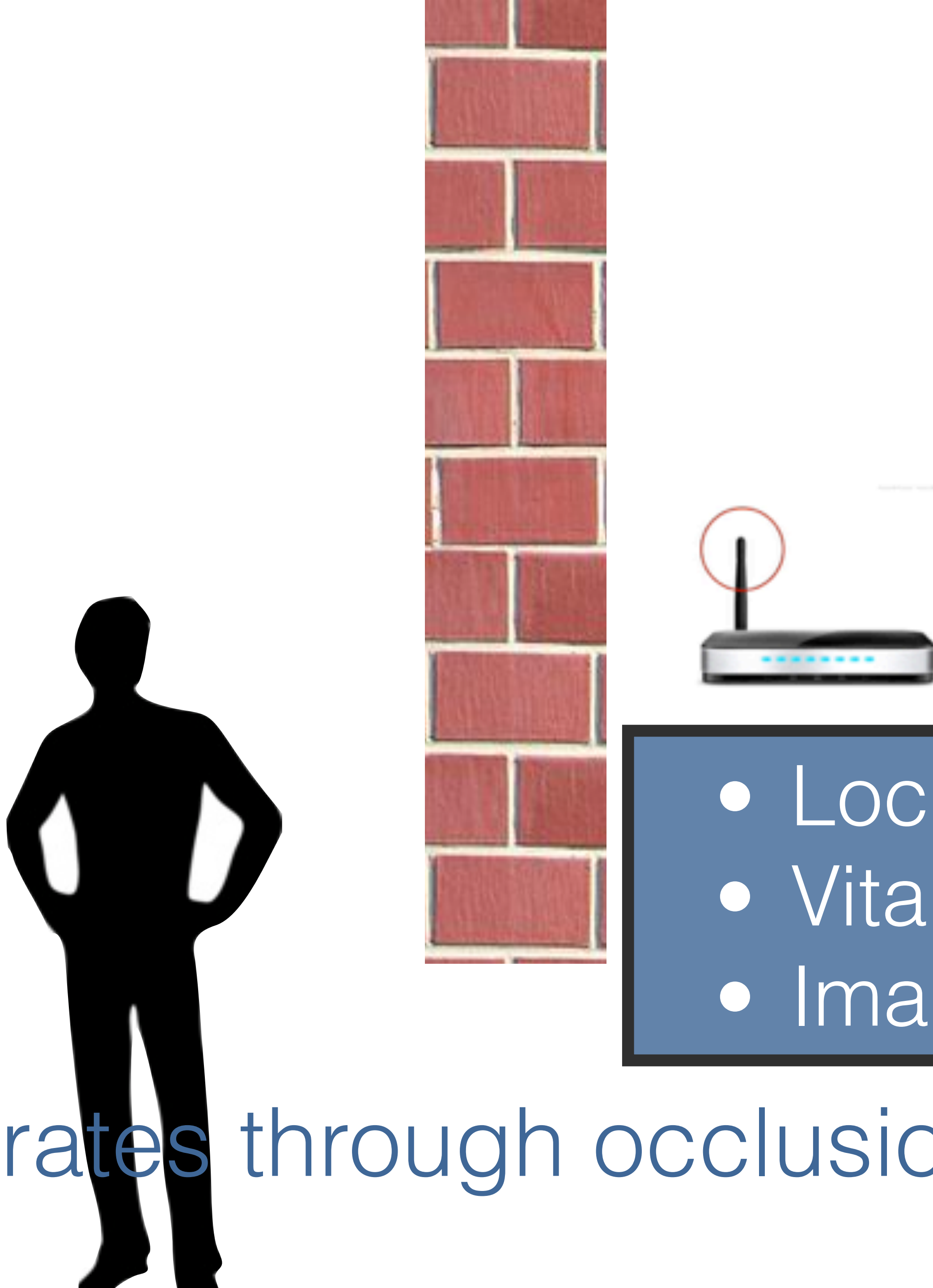
Not suitable for elderly & babies



Heart Rate | Breathing | Locations | Gestures

Imagine enabling these applications without sensors on the human body





- Location
- Vital Signs
- Imaging

Operates through occlusions

Last Lecture

WiVi: Sensing humans through walls with WiFi

- MIMO Nulling
- Inverse SAR

WiTrack: Localizing humans through walls

- FMCW
- Dynamic Multipath
- Multi-Shift FMCW
- Successive Silhouette Cancellation
- Multi-Resolution Subtraction Window

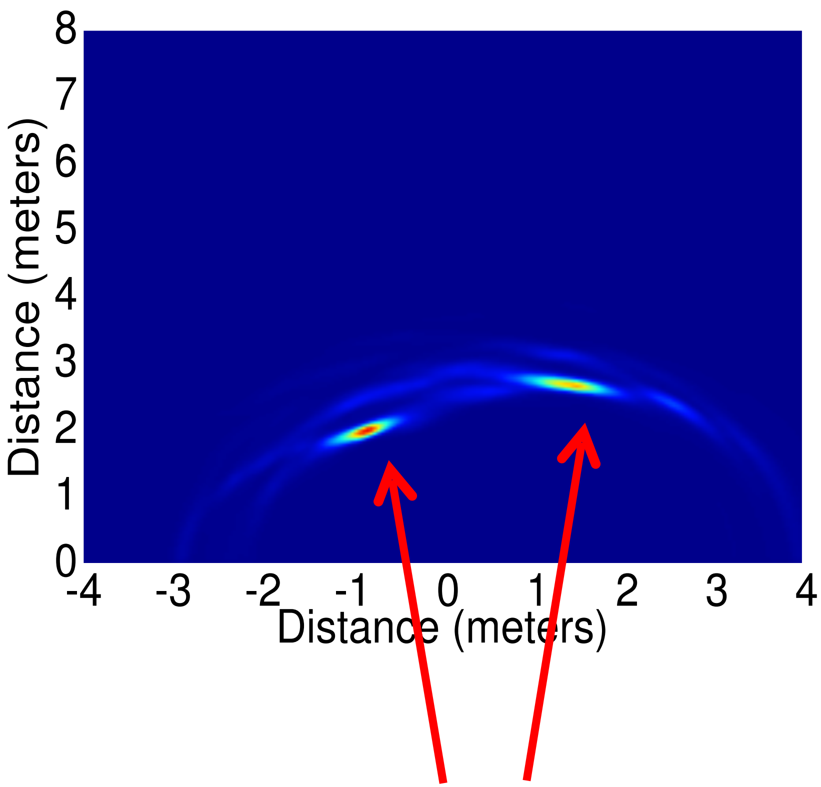
This Lecture

RF-Capture: Capturing human figure through walls

Vital Ratio: Extracting vital signs (Breathing rate and heart rate)

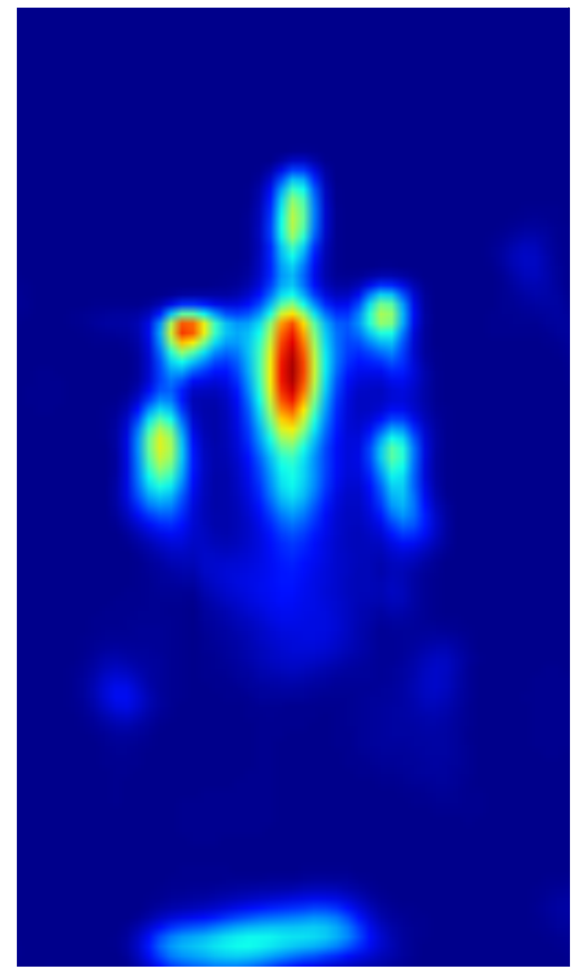
RF Imaging

People are points

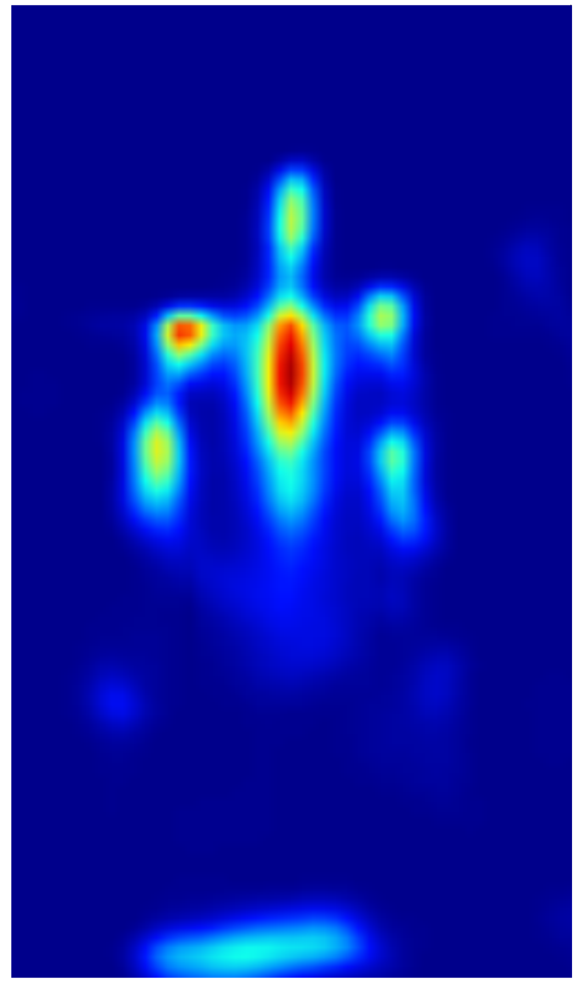


Localize the two users

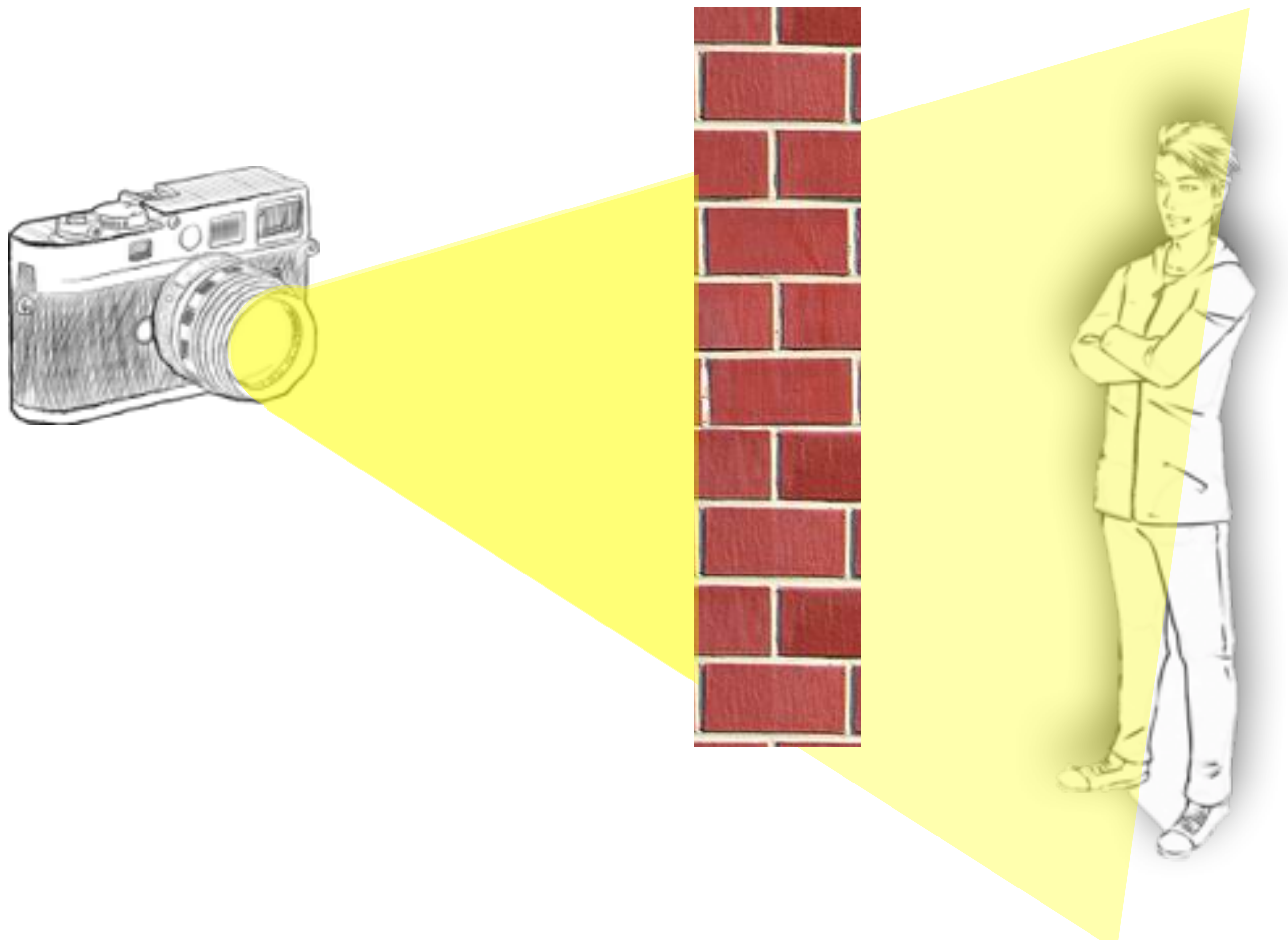
Want a silhouette



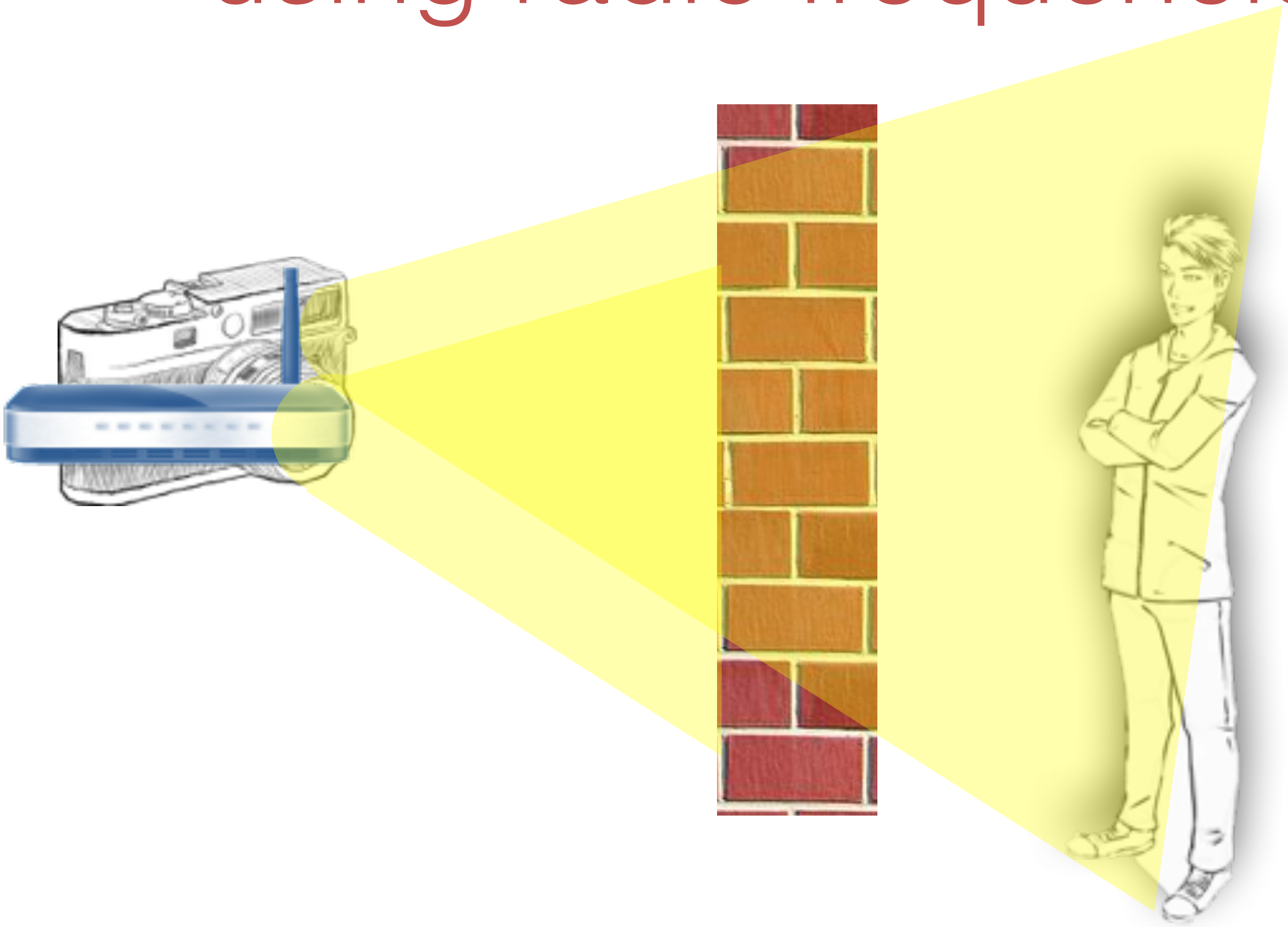
Capturing a Coarse Human Silhouette



Imaging through occlusions



Imaging through occlusions
using radio frequencies



Traditional Imaging	RF Imaging
Cannot image through occlusions like walls	+ Walls are transparent and can image through them
Form 2D images using lenses	− No lenses at these frequencies
Get a reflection from all points: can image all the body	− No reflections from most points: all reflections are specular

RF Imaging

+ Walls are transparent and can image through them

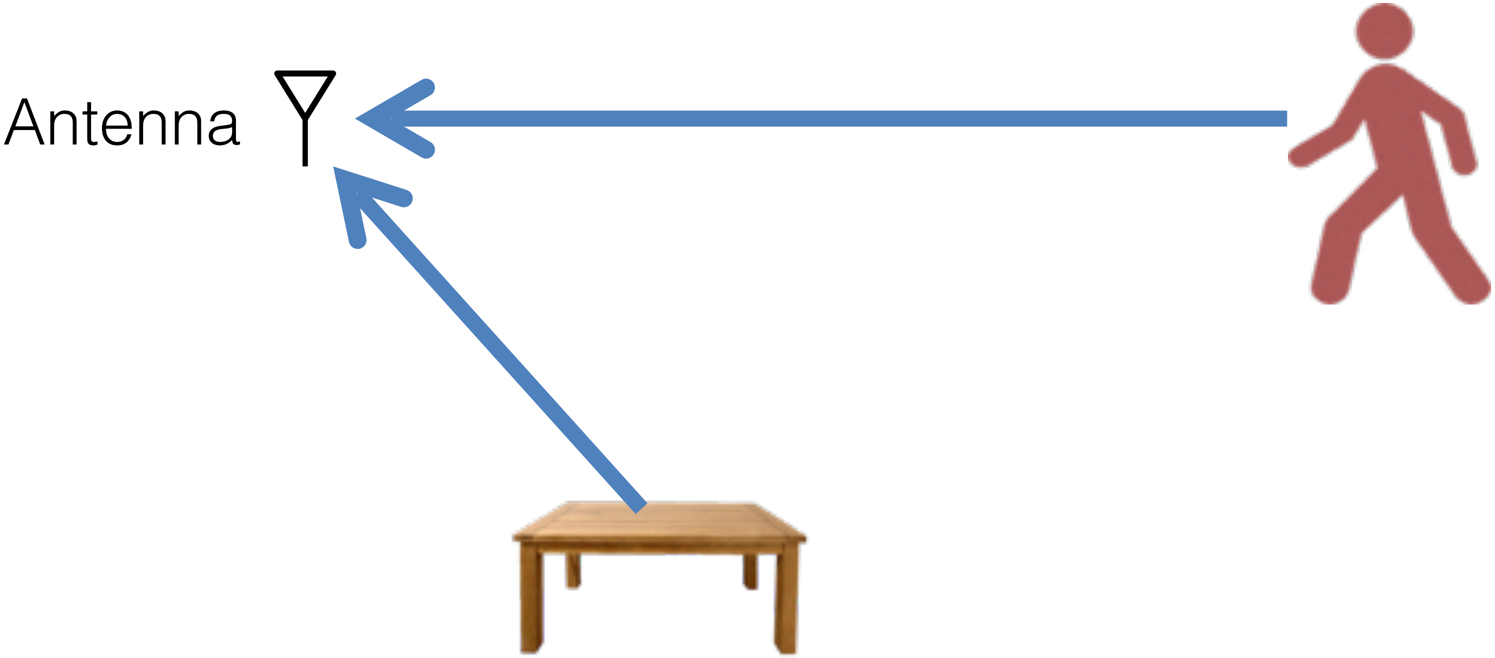
– No lenses at these frequencies → <u>Solution:</u> A component that scans 3D space with RF and outputs reflection snapshots at every point in time

– No reflections from most points: all reflections are specular → ?

Imaging with RF

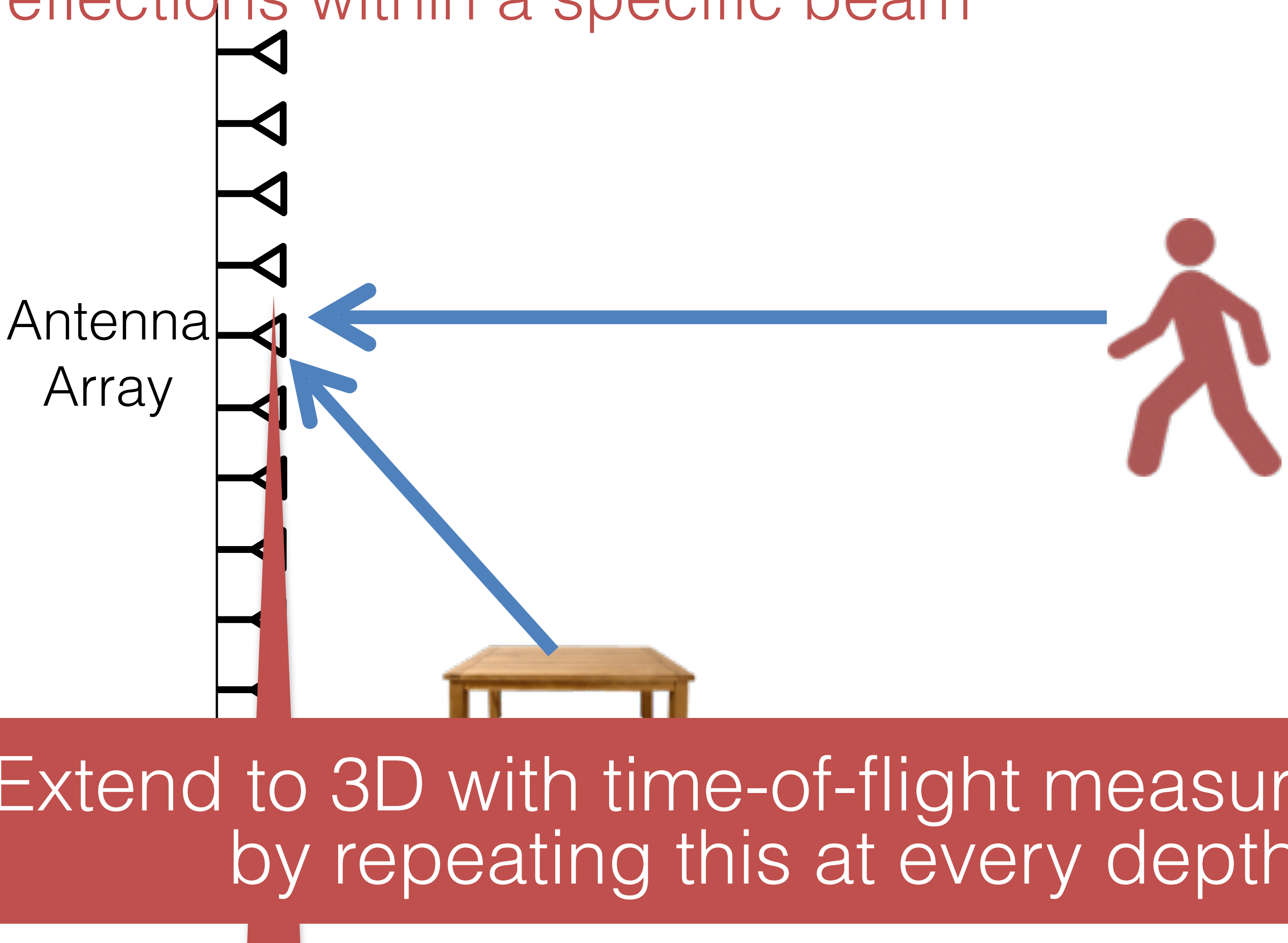
No lens at these frequencies

Antenna cannot distinguish bounces from different directions



Imaging with RF

Beamforming: Use multiple antennas to scan reflections within a specific beam



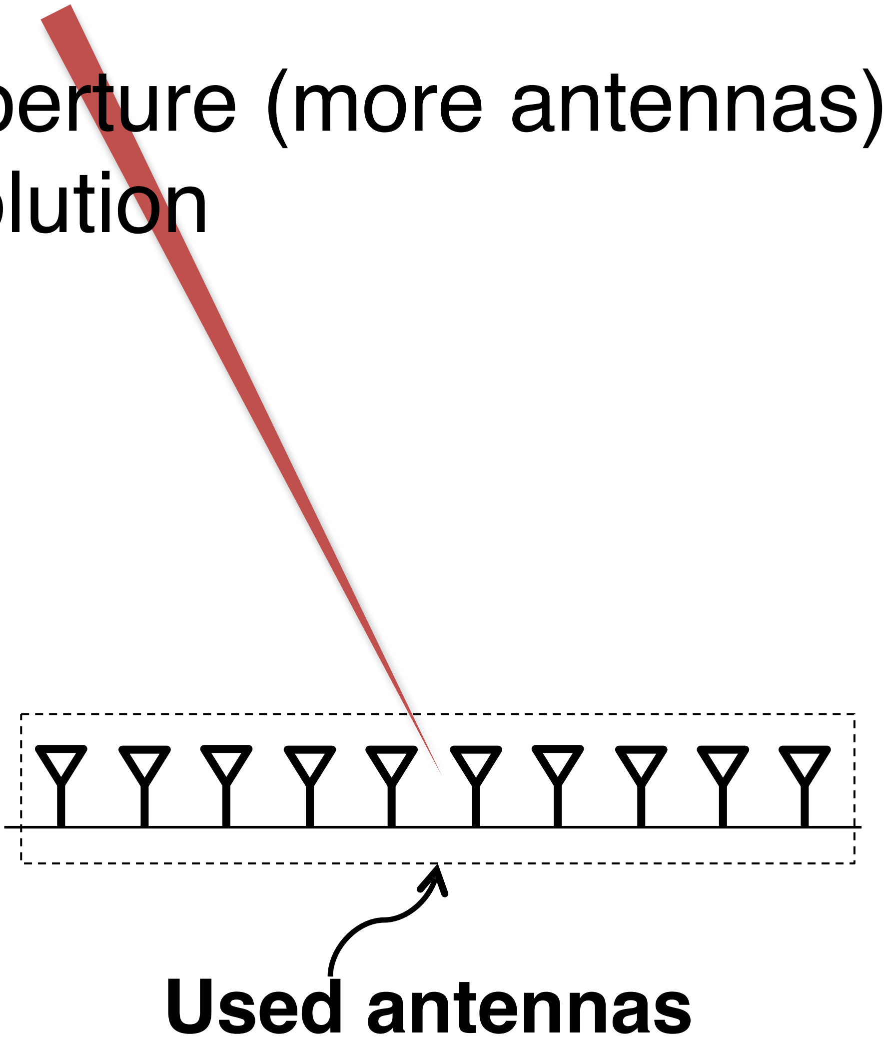
Extend to 3D with time-of-flight measurements by repeating this at every depth

Scanning every direction is slow

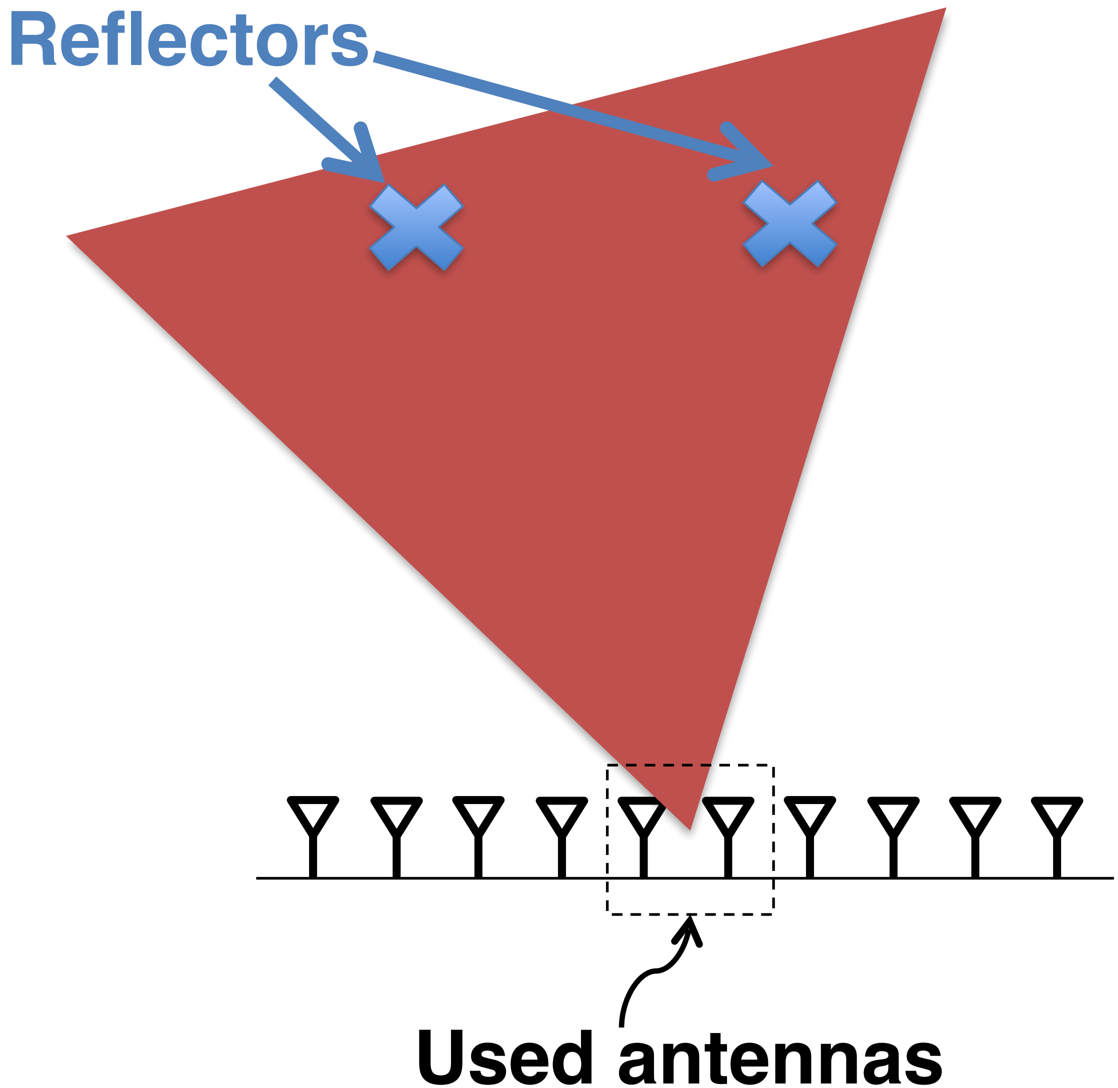
- Each angle/depth needs to be processed separately
- Most of the 3D scene is empty
- Solution: Coarse-to-fine scan that iteratively refines the resolution

Coarse-to-fine Scan

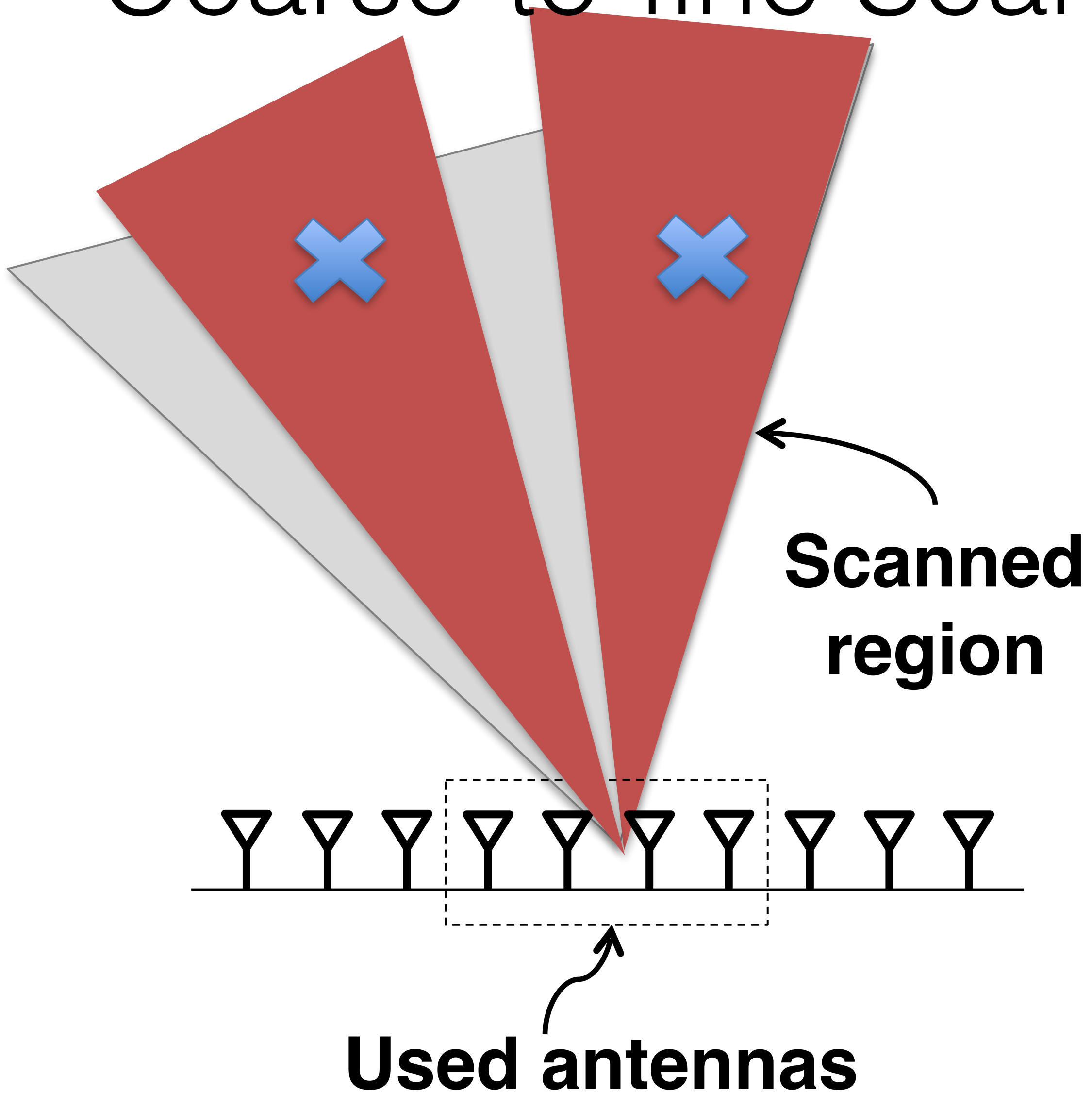
- Larger aperture (more antennas) means finer resolution



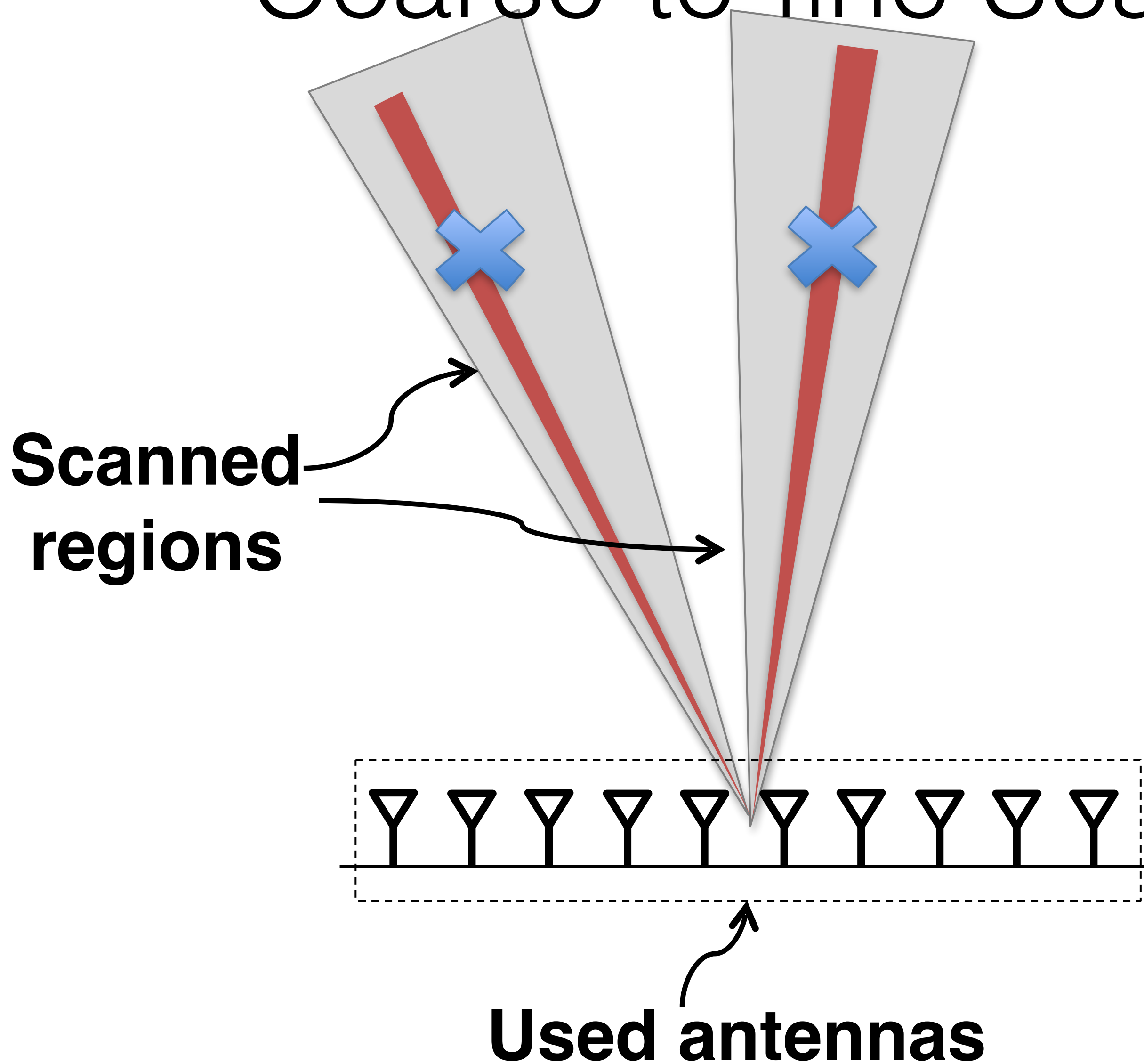
Coarse-to-fine Scan



Coarse-to-fine Scan

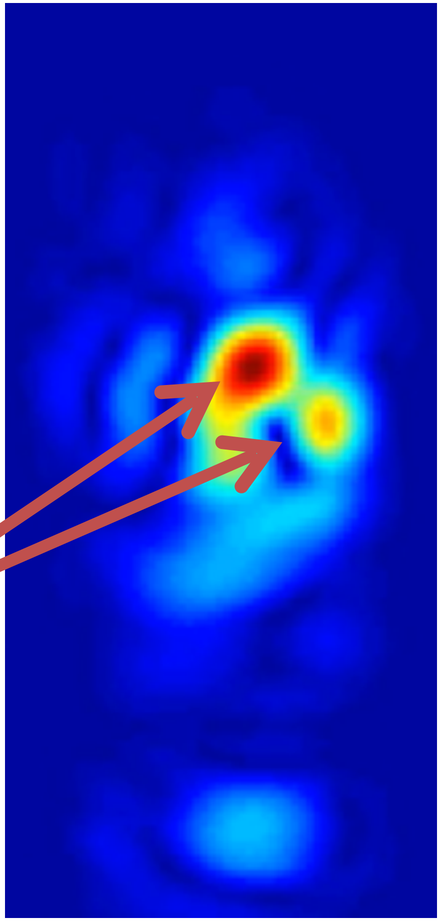


Coarse-to-fine Scan



Challenge: We only obtain blobs in space

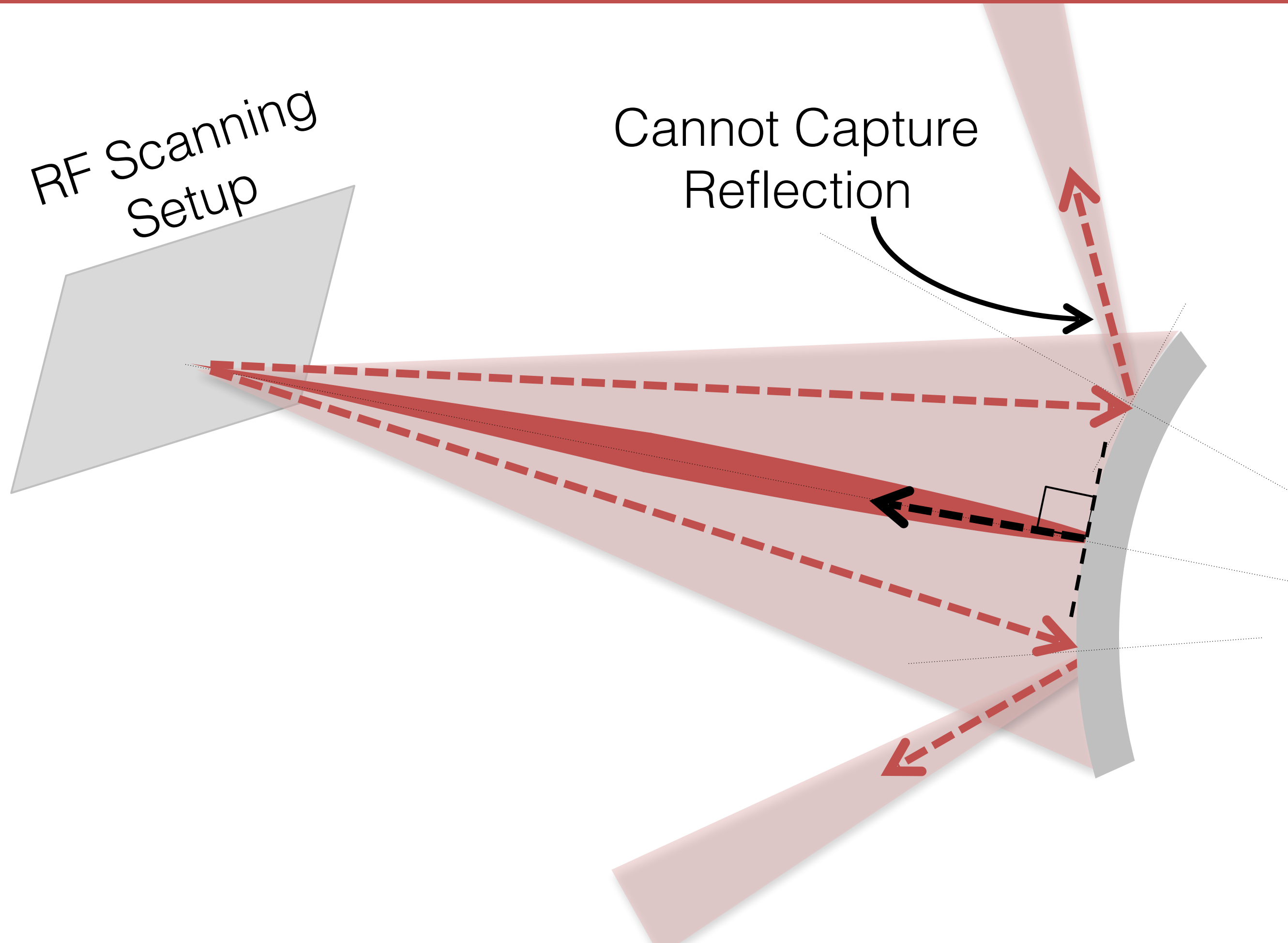
Output of 3D RF Scan



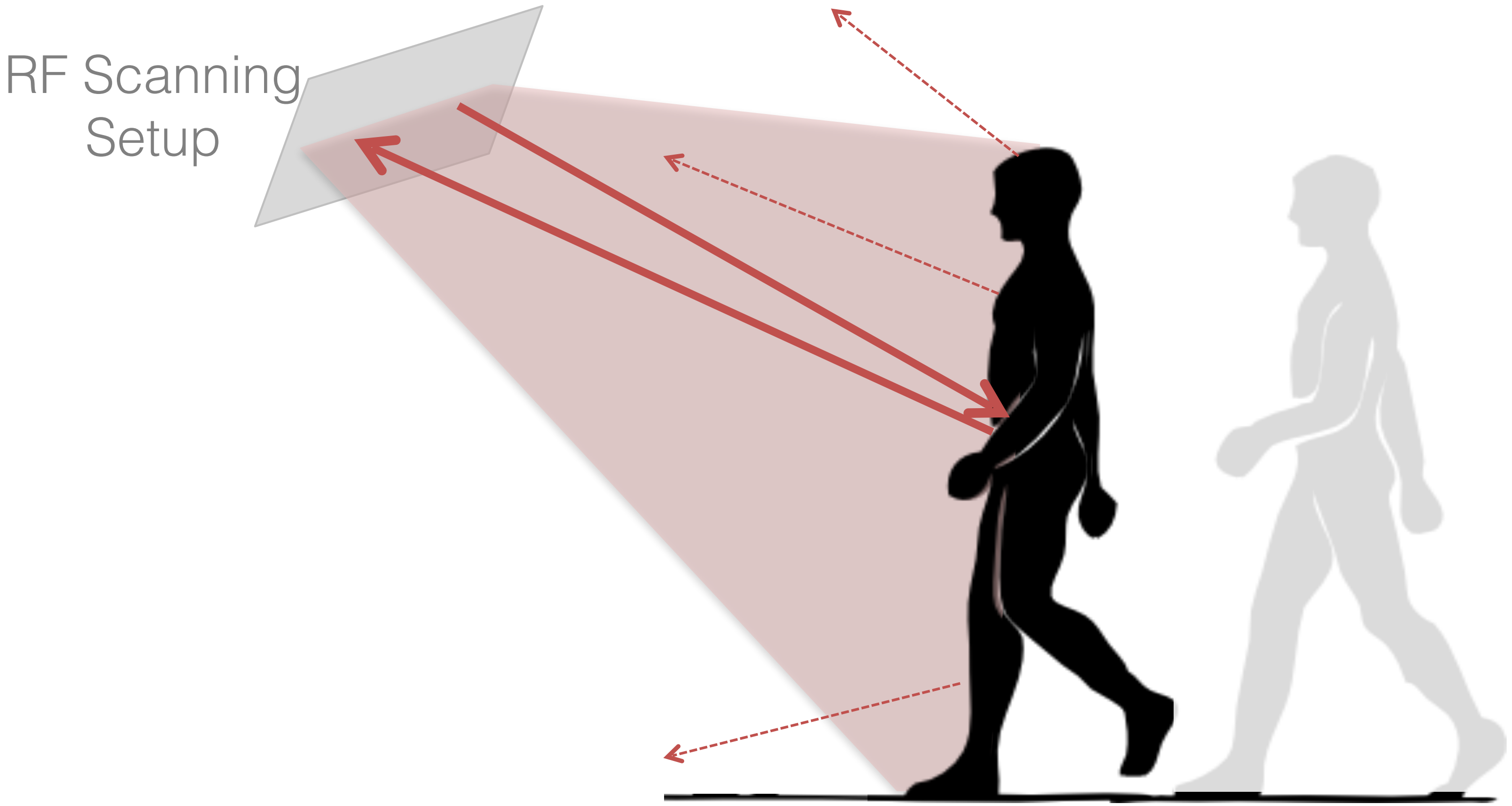
<u>Challenge:</u> Don’t get reflections from most points in RF

At frequencies that traverse walls, human body parts are specular **(pure mirror)**

At every point in time, we get reflections from only a subset of body parts.



Solution Idea: Exploit Human Motion and Aggregate over Time



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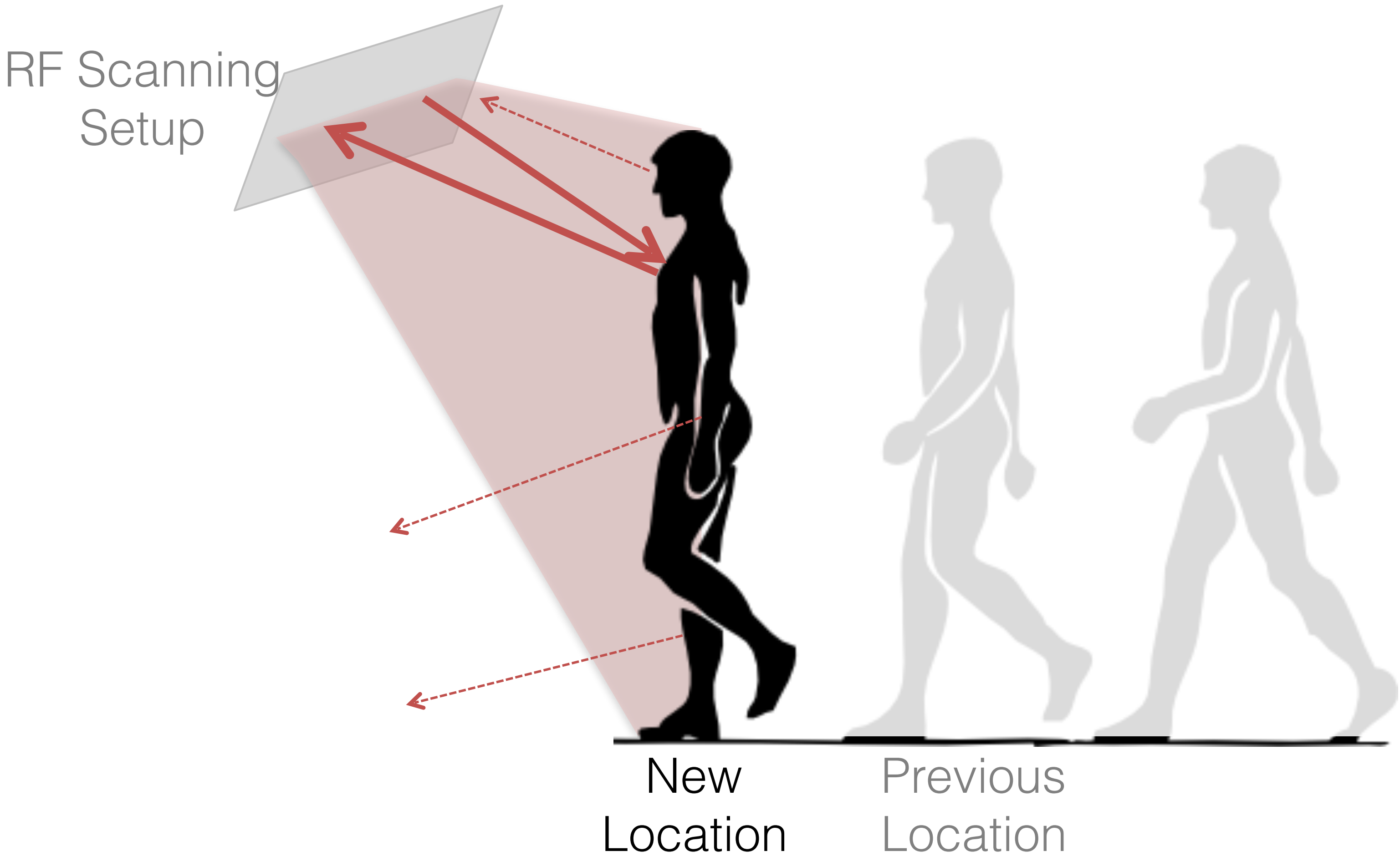
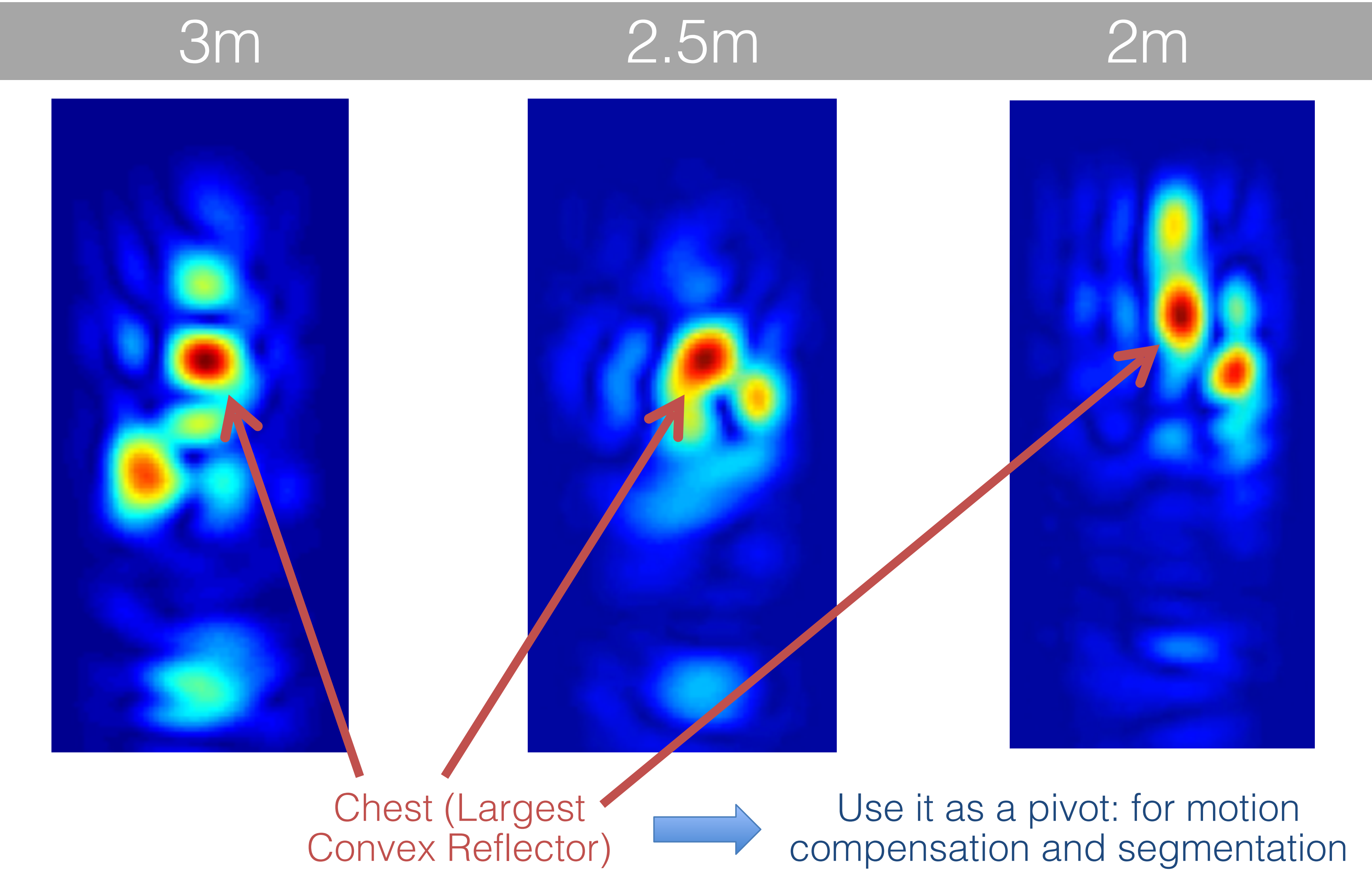


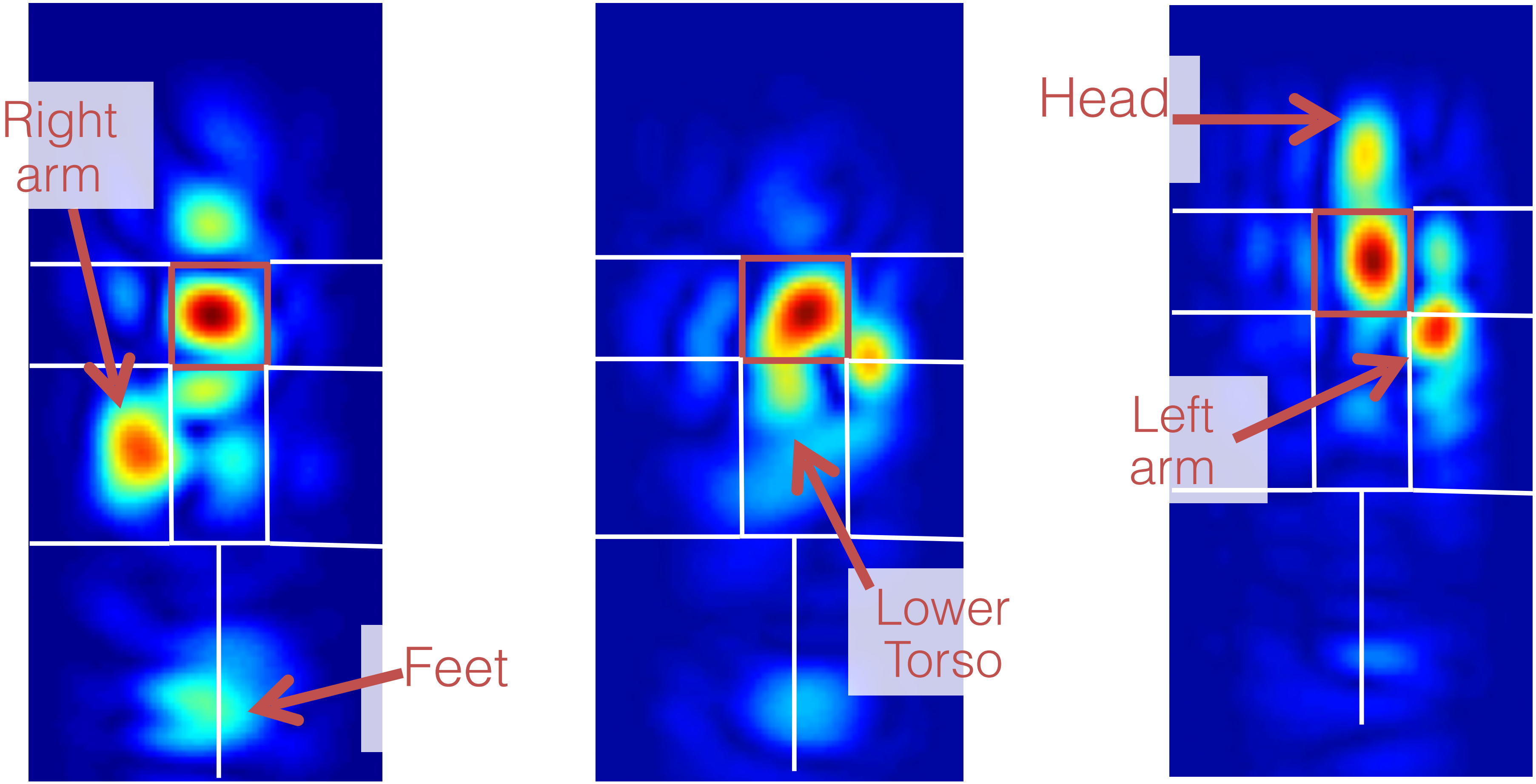
Combine the various snapshots

Human Walks toward Sensor



Human Walks toward Sensor

3m	2.5m	2m

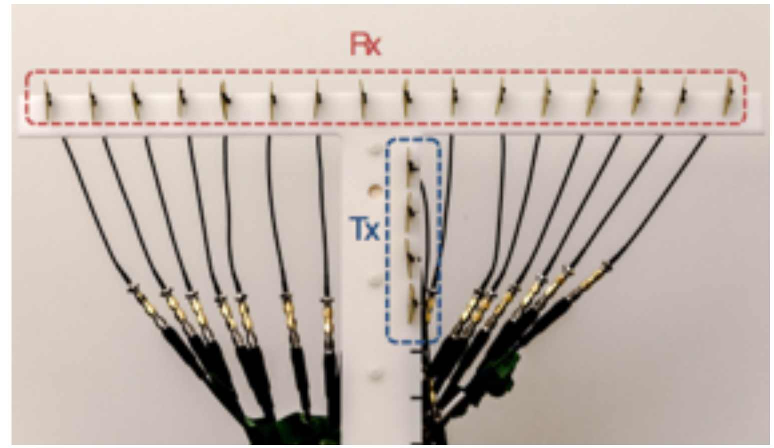


Combine the various snapshots

Human Walks toward Sensor

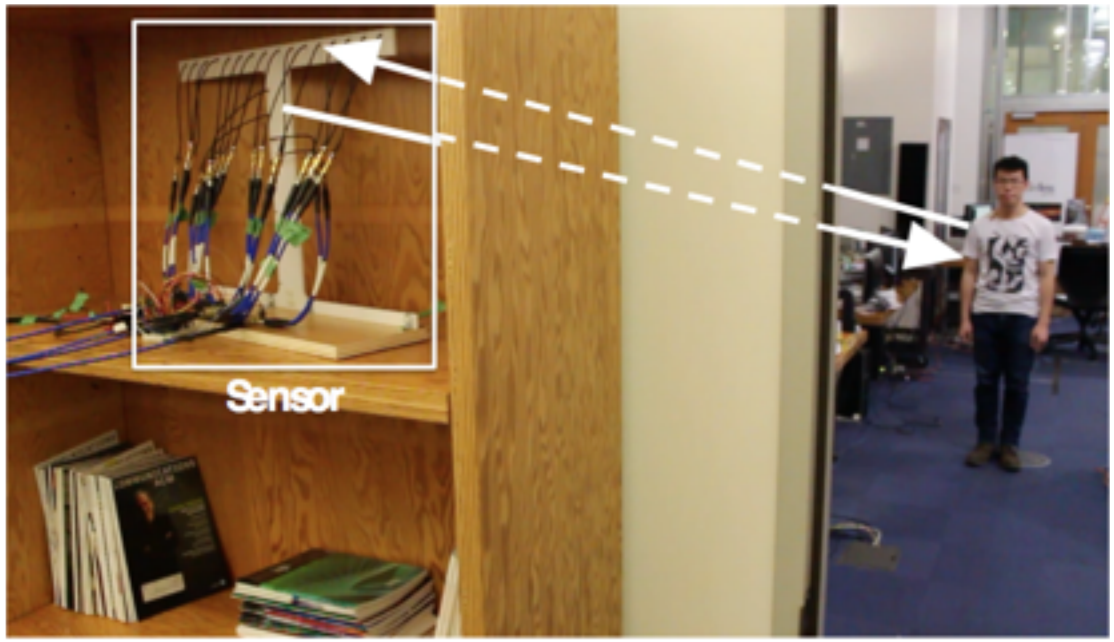
Implementation

- Hardware
  - 2D Antenna Array
  - Built RF circuit
    - 1/1,000 power of WiFi
    - USB connection to PC



- Software
  - Coarse-to-fine algorithm implemented in GPU to generate reflection snapshots in real-time

Evaluation

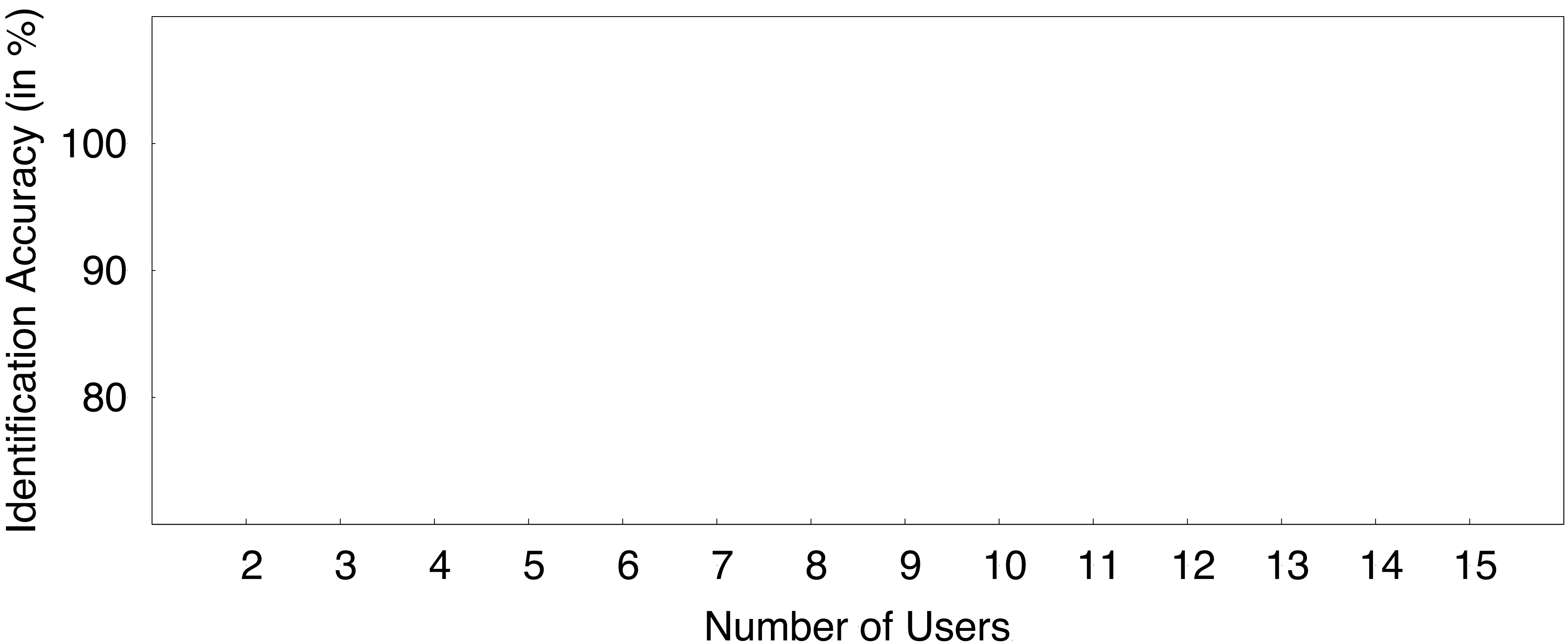


- RF-Capture sensor placed behind the wall
- 15 participants
- Use Kinect as baseline when needed

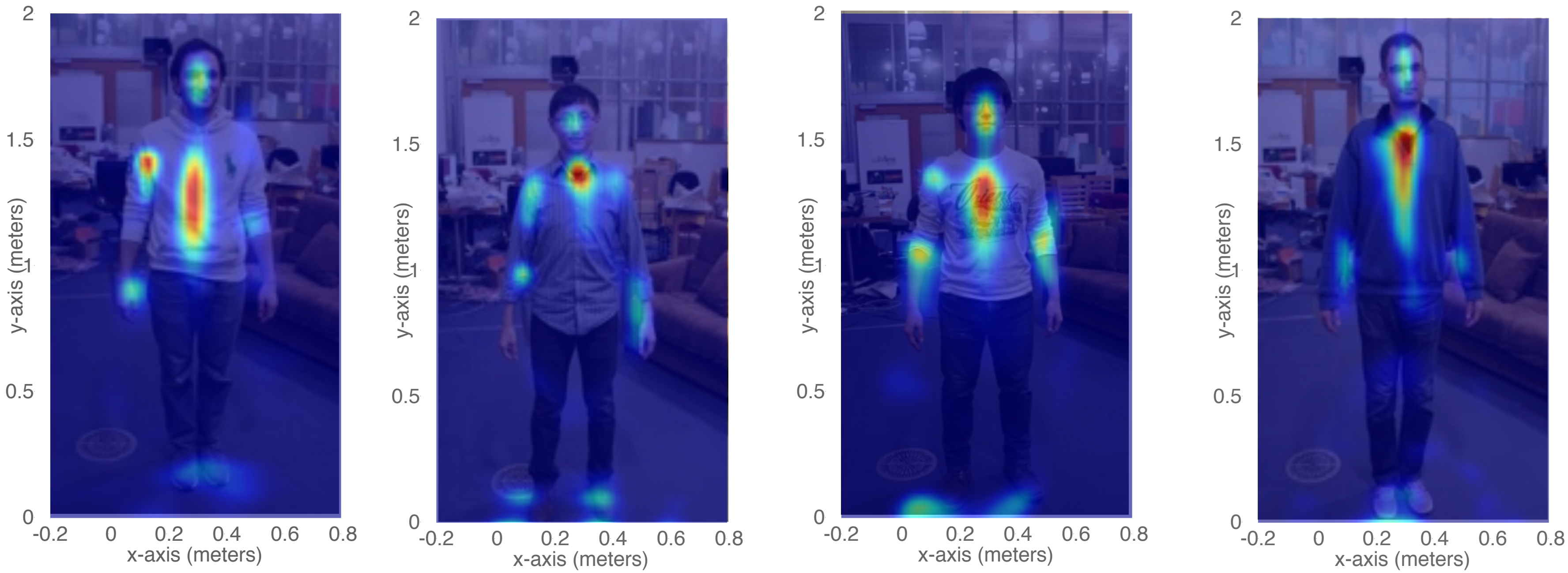
Distinguishing Among Subjects

Experiment: Subjects walk to device behind wall

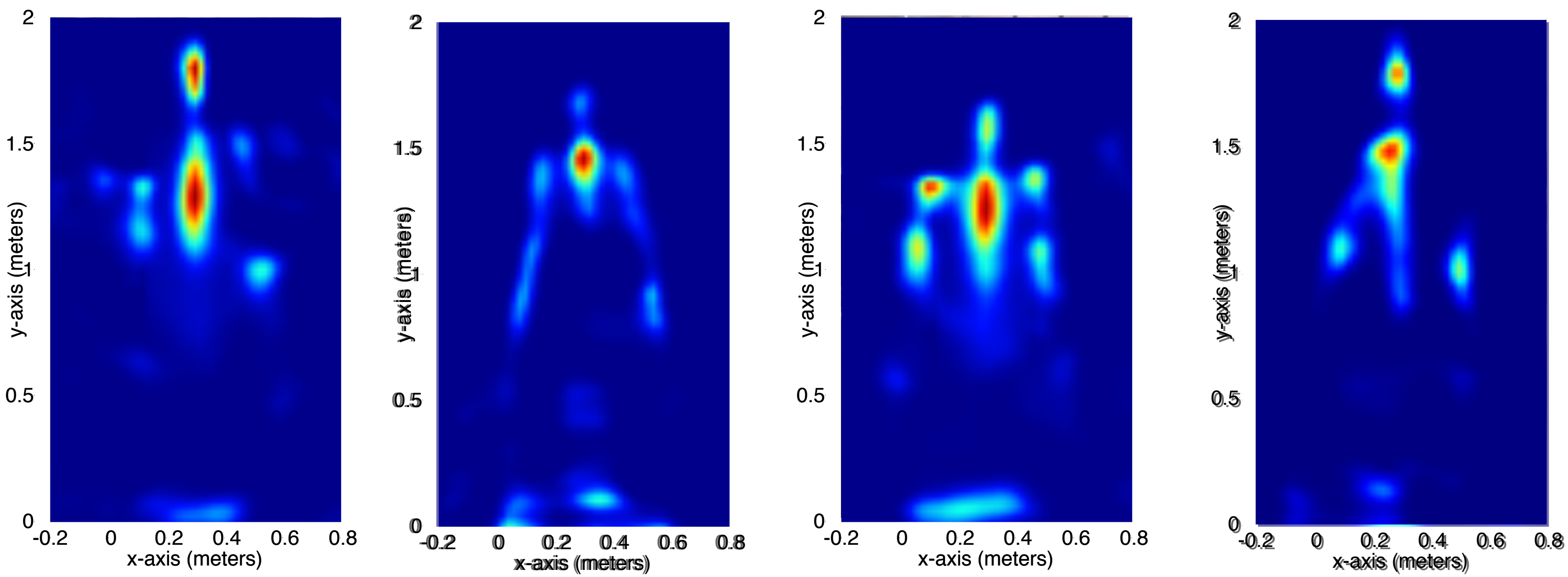
Training: PCA+SVM on captured figures



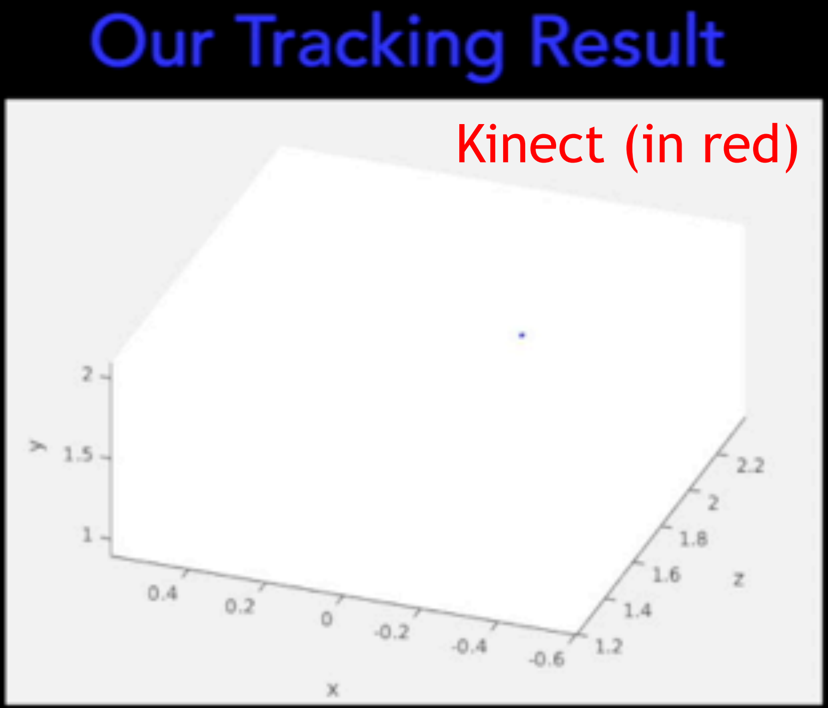
Sample Captured Figures through Walls



Through-wall classification accuracy of 90% among 13 users



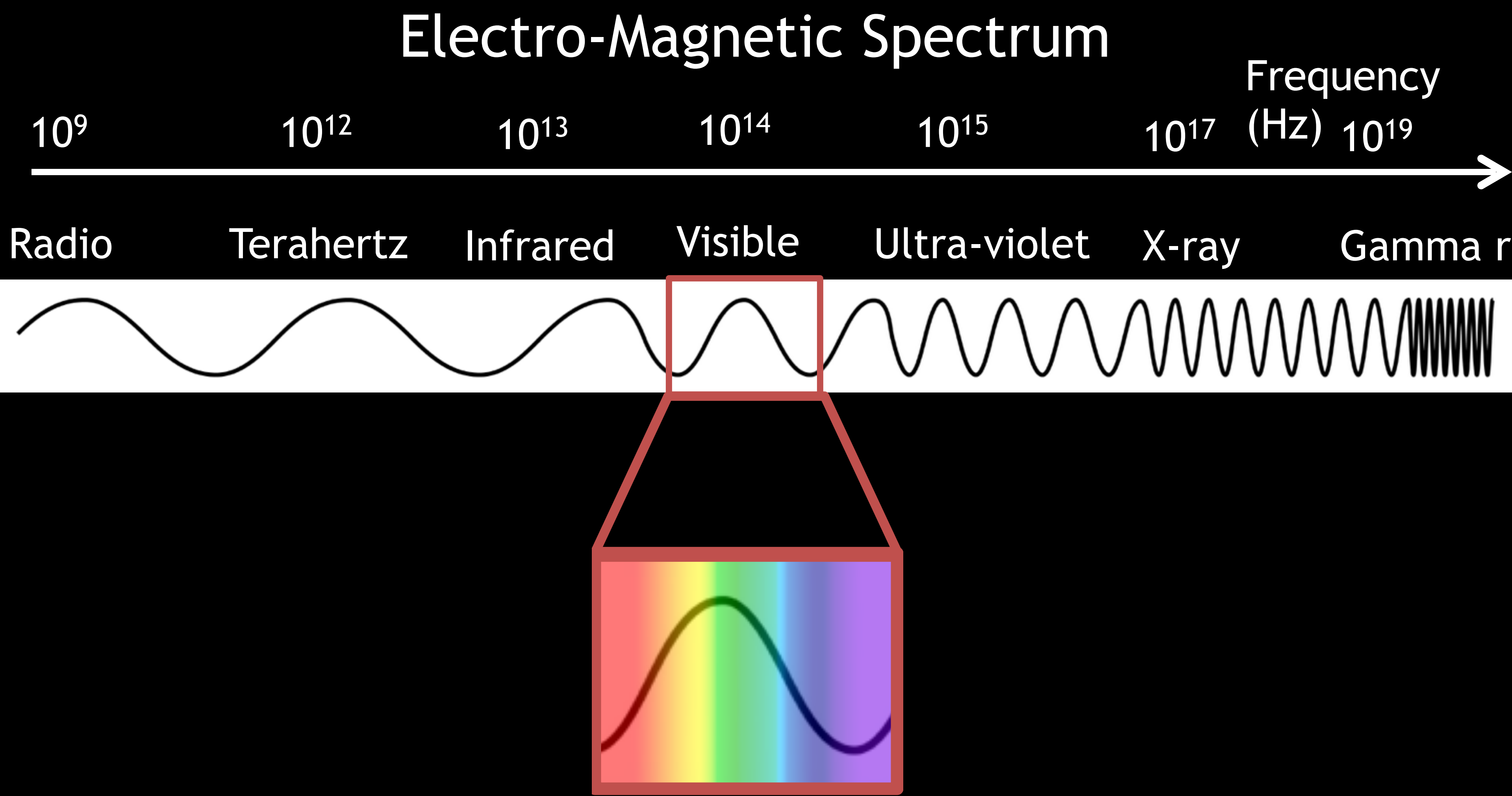
Writing in the air



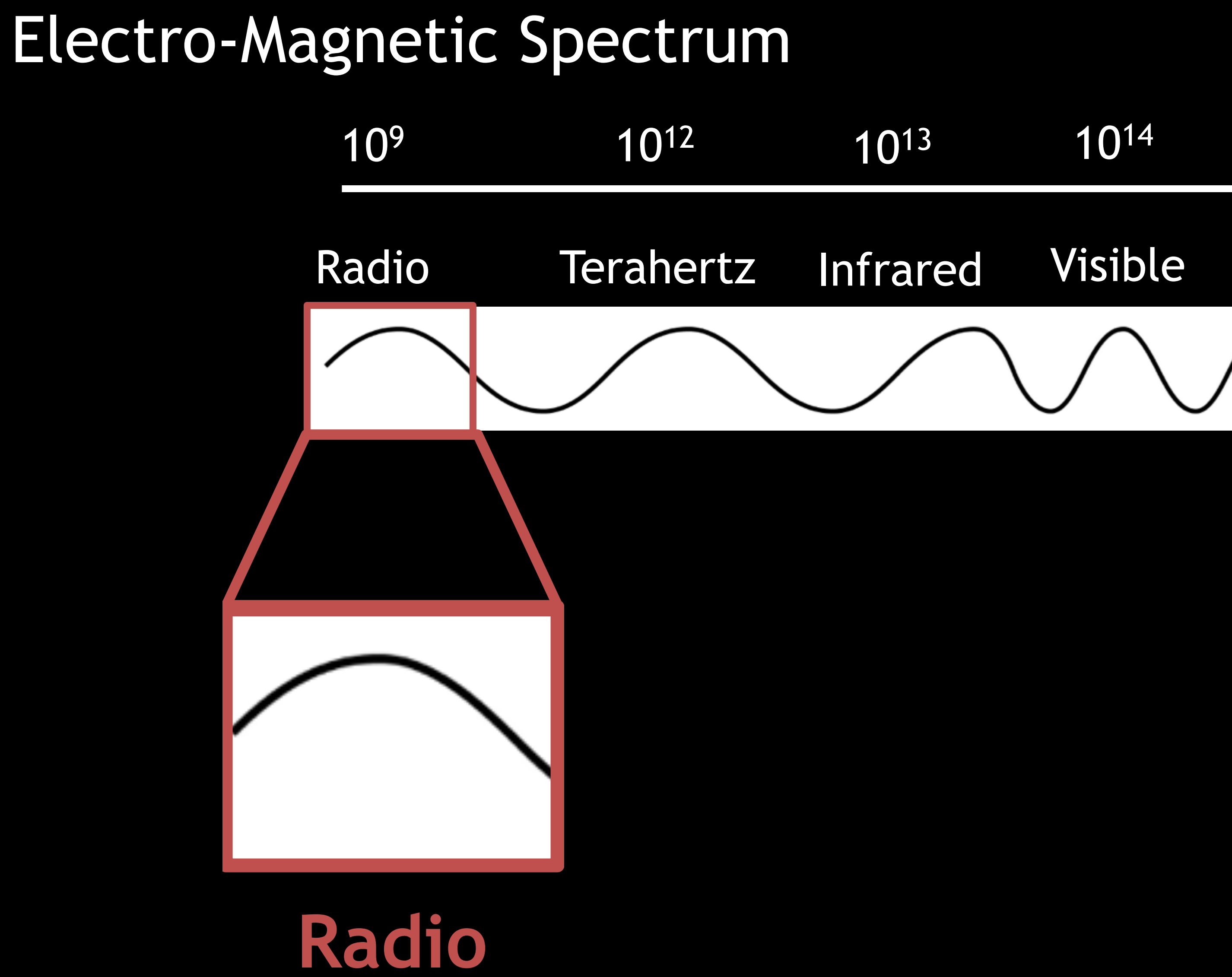
Median Accuracy is 2cm

Access to a new type of visual information by RF

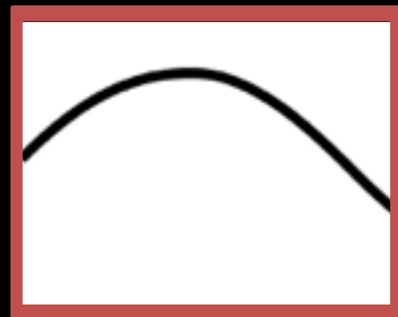
Access to a new type of visual information by RF



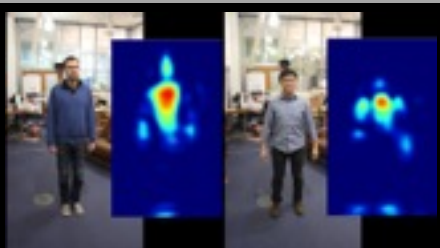
Access to a new type of visual information by RF



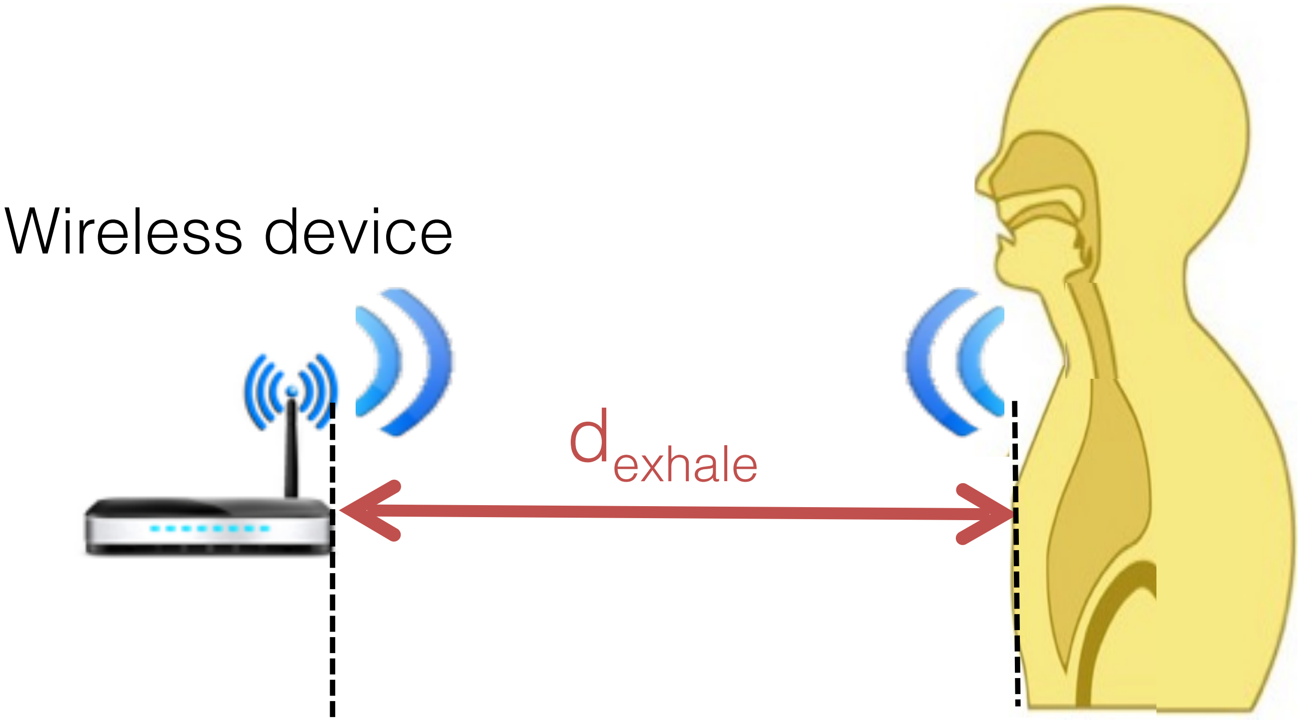
Access to a new type of visual information by RF



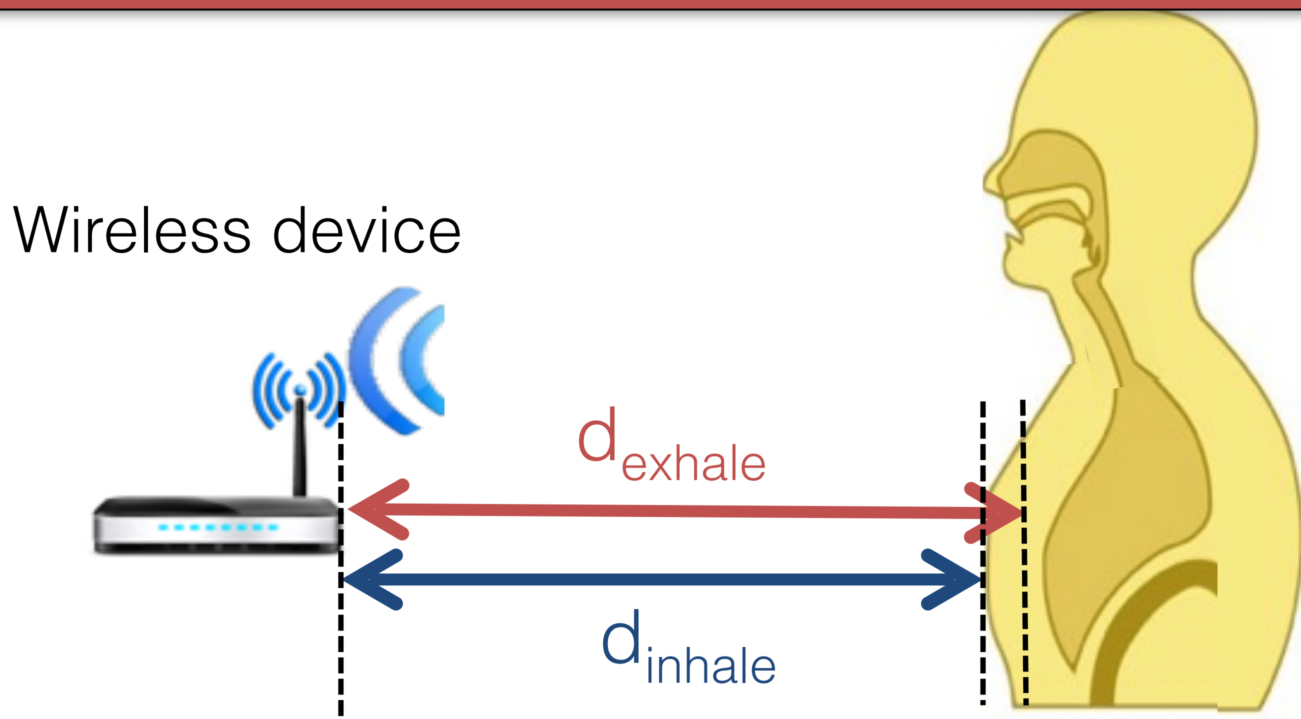
Radio

Applications	Challenges	Limitations
 	• Achieving Sufficient Resolution • Dealing with Specularity	Limited Spatial & Temporal Resolution

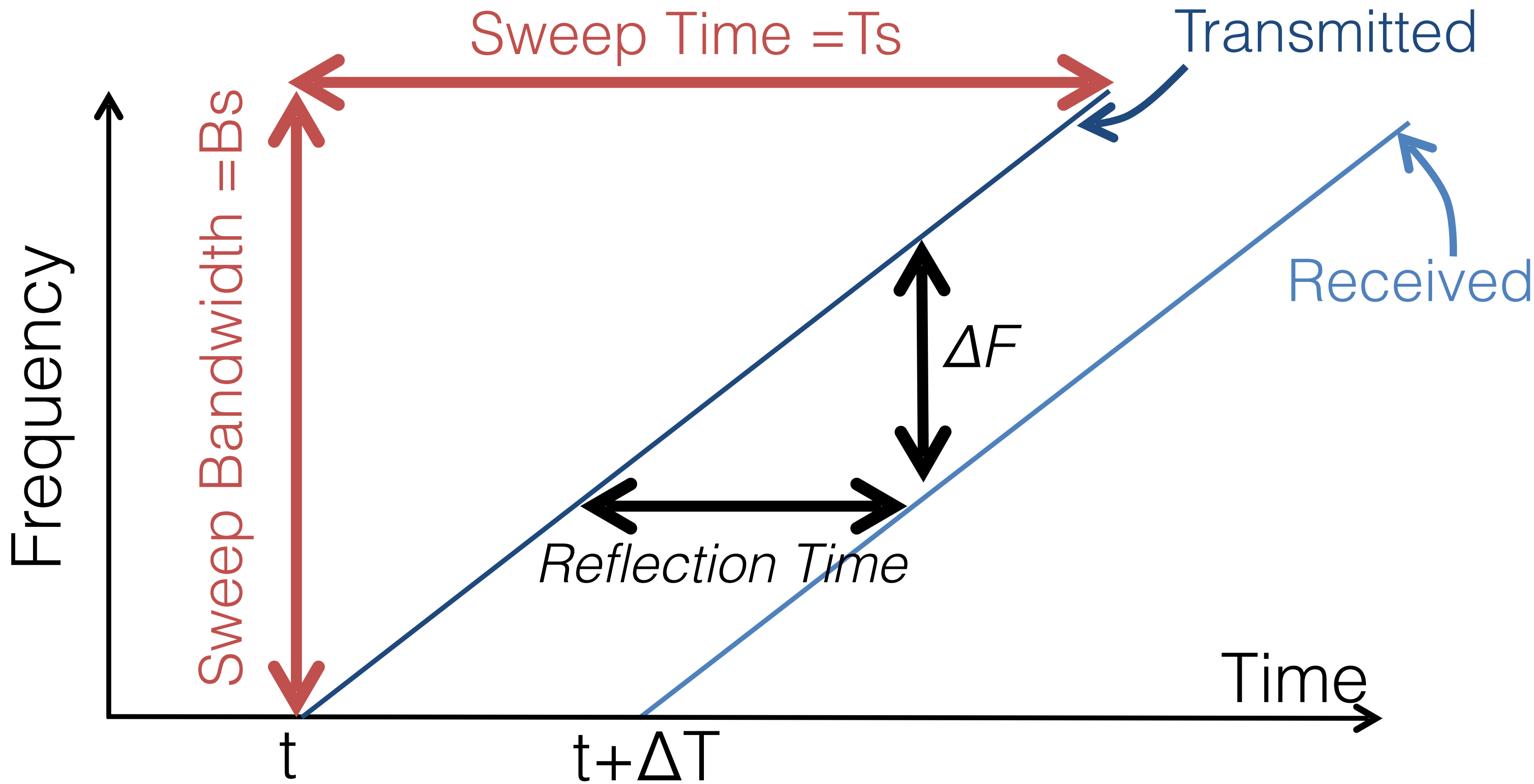
Vital Radio: Use wireless reflections off the human body to monitor breathing and heart rate


Wireless device
d_{exhale}

<u>Problem:</u> Localization accuracy is only 12cm and cannot capture vital signs



FMCW: Measure time by measuring frequency



Slope = k = Bs/Ts

Reflection Time =ΔF/k

FMCW

- FMCW Transmitted Signal:

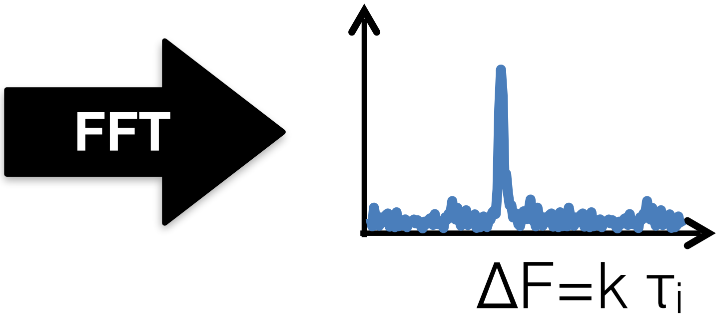
$$x(t) = e^{j2\pi(\frac{k}{2}(t^2+f_0 t))}$$

- FMCW Received Signal:

$$y(t) = \sum_i A_i e^{j2\pi(\frac{k}{2}((t-\tau_i)^2+f_0(t-\tau_i)))}$$

- FMCW after downconversion:

$$y_b(t) = \sum_i A_i e^{j2\pi(k\tau_i t+f_0\tau_i)}$$



- Sampling Rate = R

$\Delta F < R \longrightarrow \tau_{max} = R/k = RxTs/Bs \longrightarrow d_{max} = cxRxTs/2Bs$

FMCW

- FMCW Transmitted Signal:

$$x(t) = e^{j2\pi(\frac{k}{2}(t^2+f_0 t))}$$

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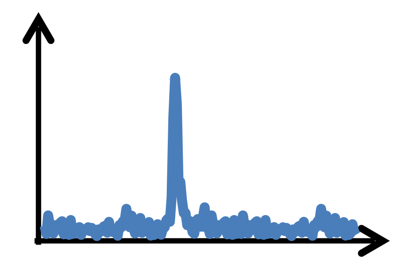
FFT →



$\Delta F = k\,\tau_i$

- Sampling Rate = R

$\Delta F < R \longrightarrow \tau_{max} = R/k = RxTs/Bs \longrightarrow d_{max} = cxRxTs/2Bs$

- Sampling Window = Ts

$dF > 1/Ts \longrightarrow \tau_{min} = 1/(kxTs) = 1/Bs \longrightarrow d_{min} = c/2Bs$

FMCW

- FMCW Transmitted Signal:

$$x(t) = e^{j2\pi(\frac{k}{2}(t^2+f_0 t))}$$

- FMCW Received Signal:

$$y(t) = \sum_i A_i e^{j2\pi(\frac{k}{2}((t-\tau_i)^2+f_0(t-\tau_i)))}$$

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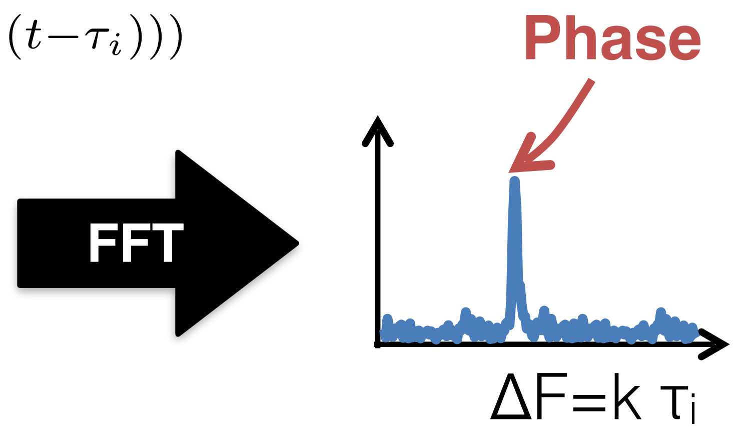


- Phase of peak = $f_0\tau_i$
    - Phase wraps around 2pi
    - Use peak position $\Delta F = k\,\tau_i$ for course estimate of τ_i
    - Use peak phase $f_0\tau_i$ for fine estimate of τ_i

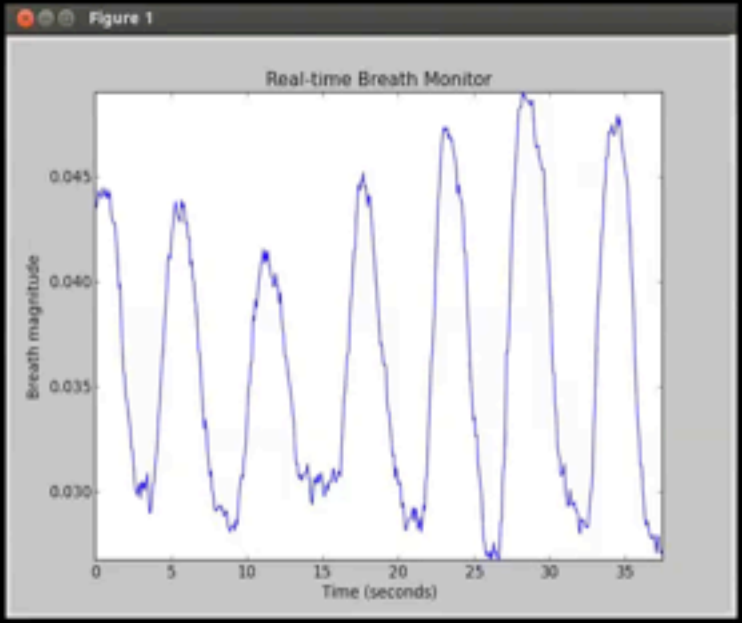
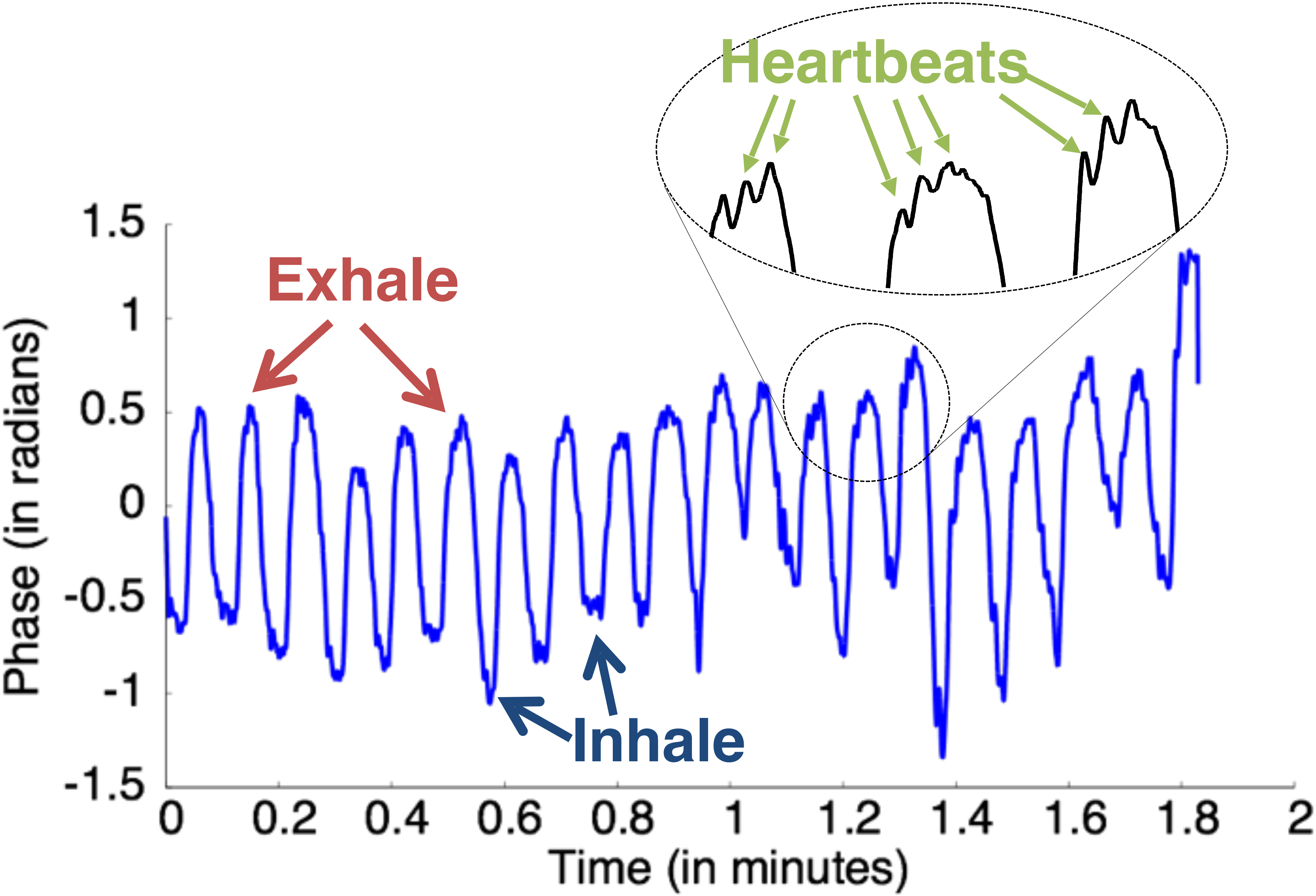


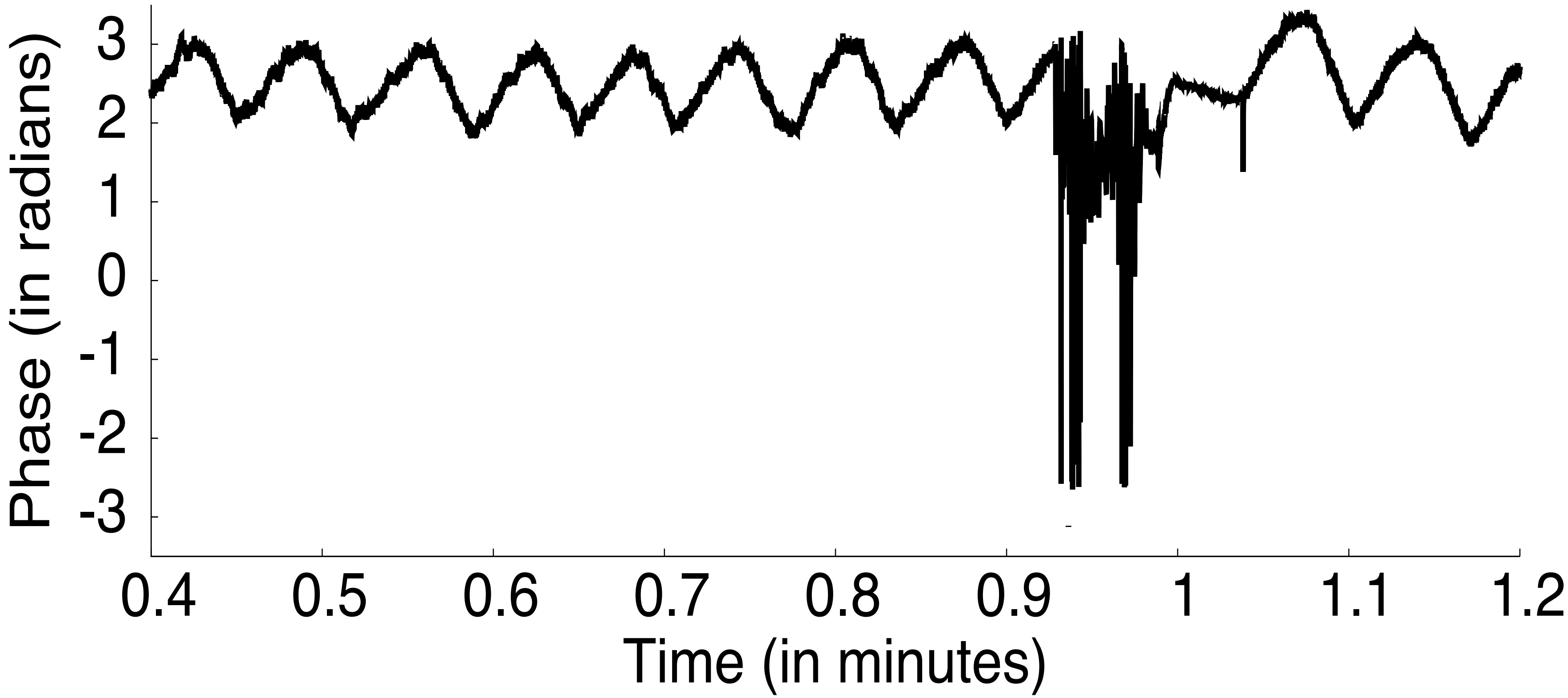
Figure 1
Real-time Breath Monitor
Breath magnitude
0.030
0.035
0.040
0.045
Time (seconds)
0
5
10
15
20
25
30
35

Let’s zoom in on these signals

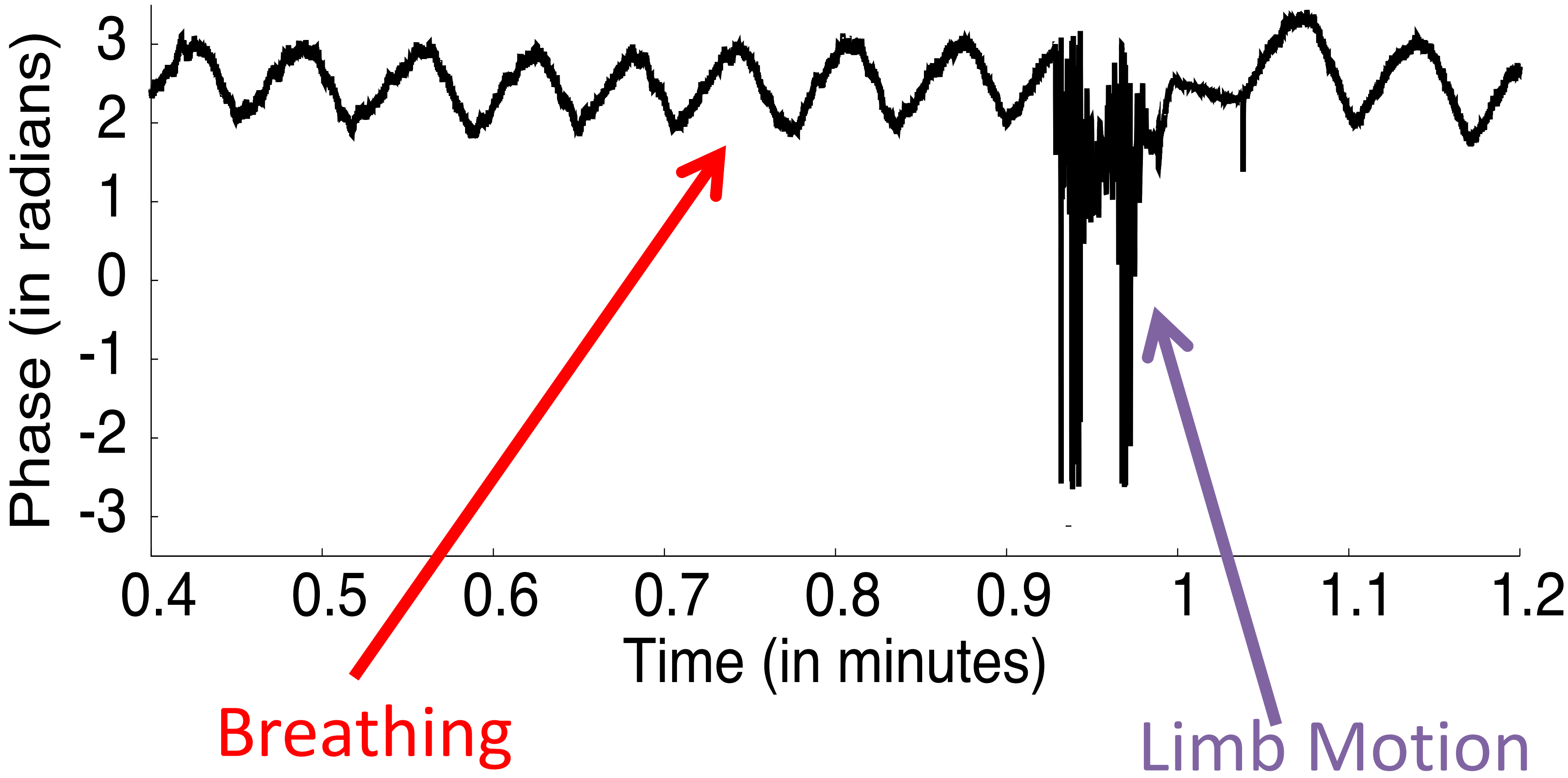

Heartbeats
Exhale
Inhale
Phase (in radians)
Time (in minutes)
1.5
1
0.5
0
-0.5
-1
-1.5
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

What happens when a person moves his limb?

What happens when a person moves his limb?



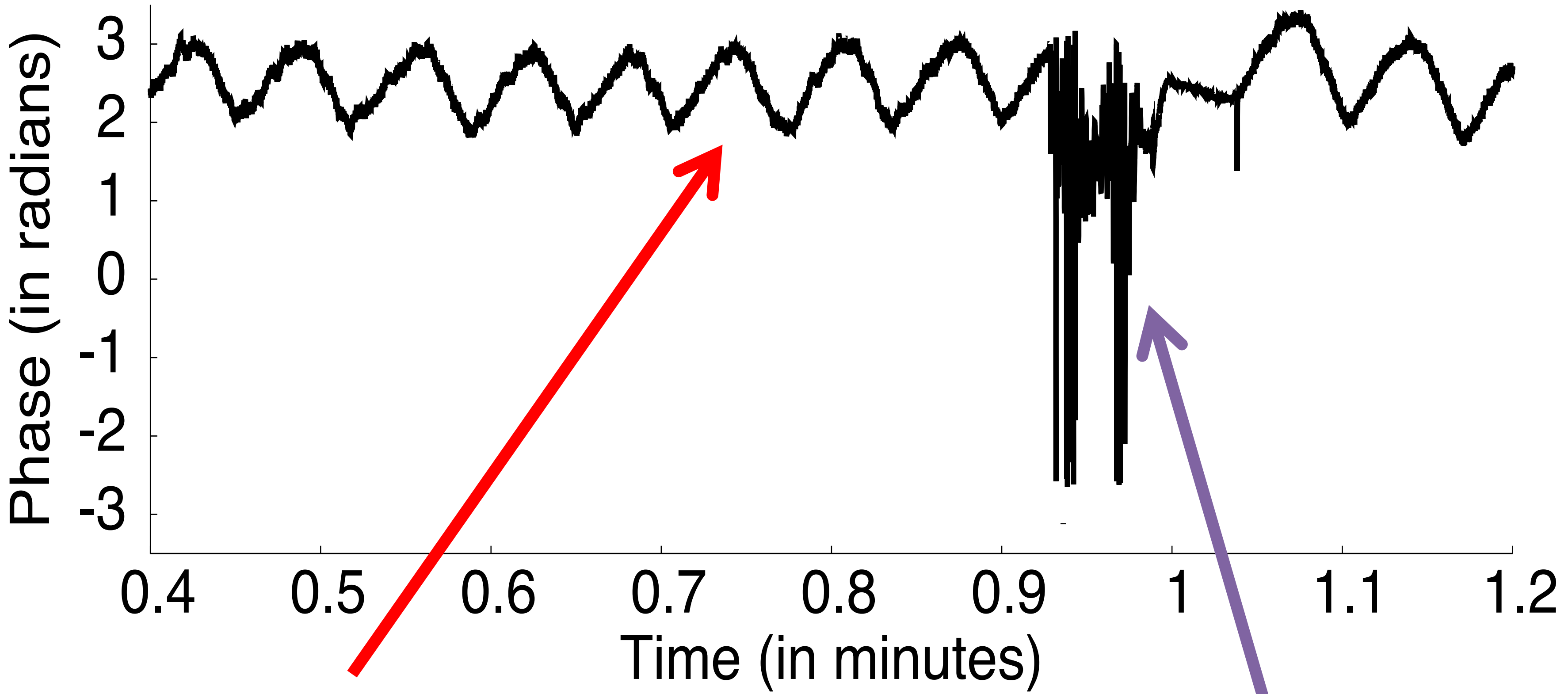
What happens when a person moves his limb?



Periodic

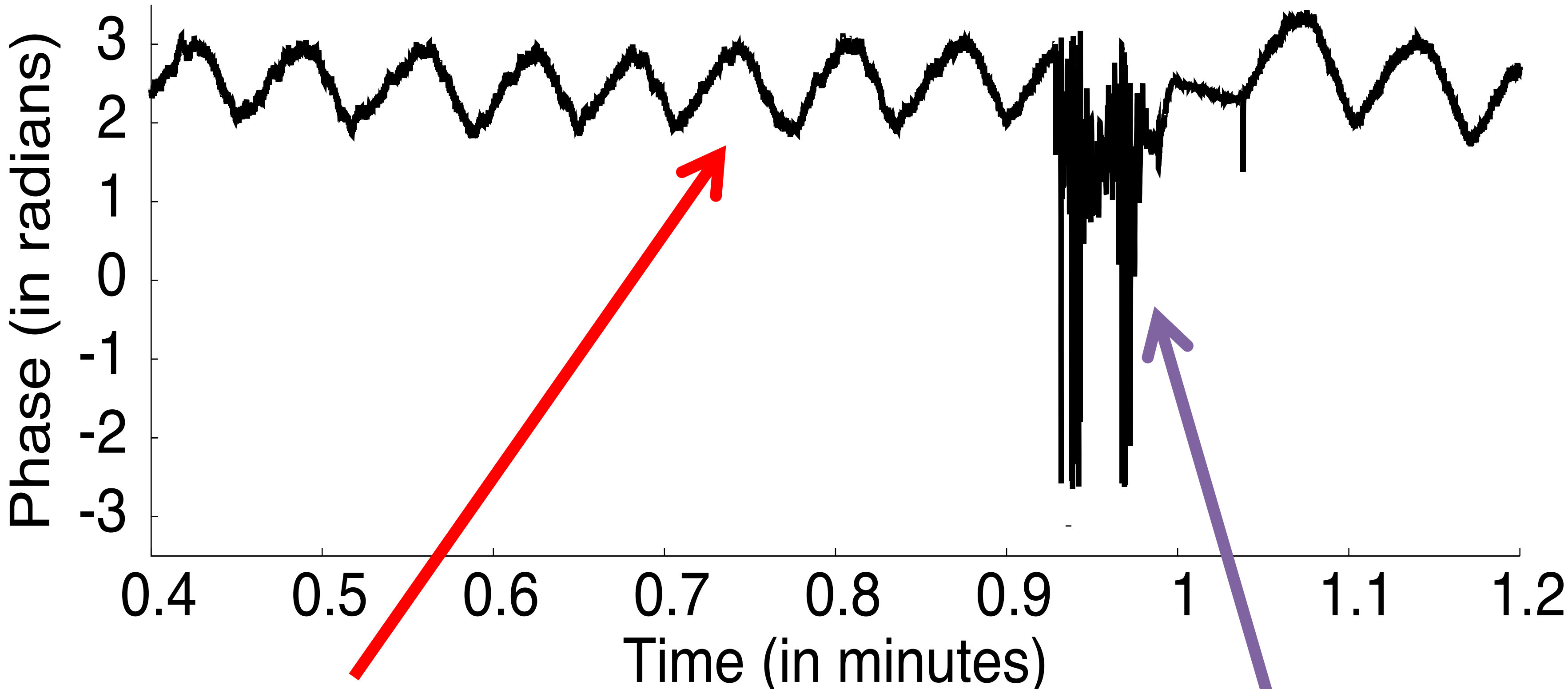
Not periodic

What happens when a person moves his limb?



Use periodicity test to eliminate variations that are not due to breathing/heartbeats

What happens when a person moves his limb?

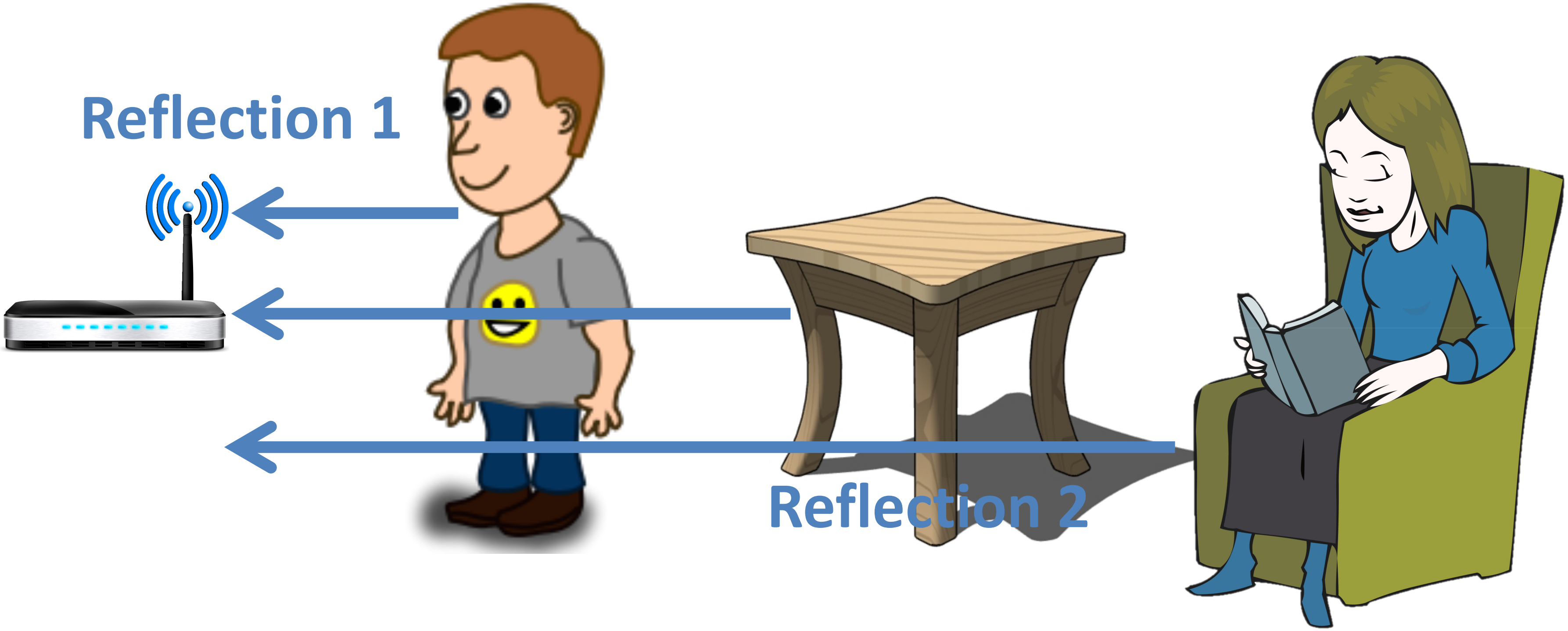


Band-pass filter the cleaned signals to extract breathing and heart rate

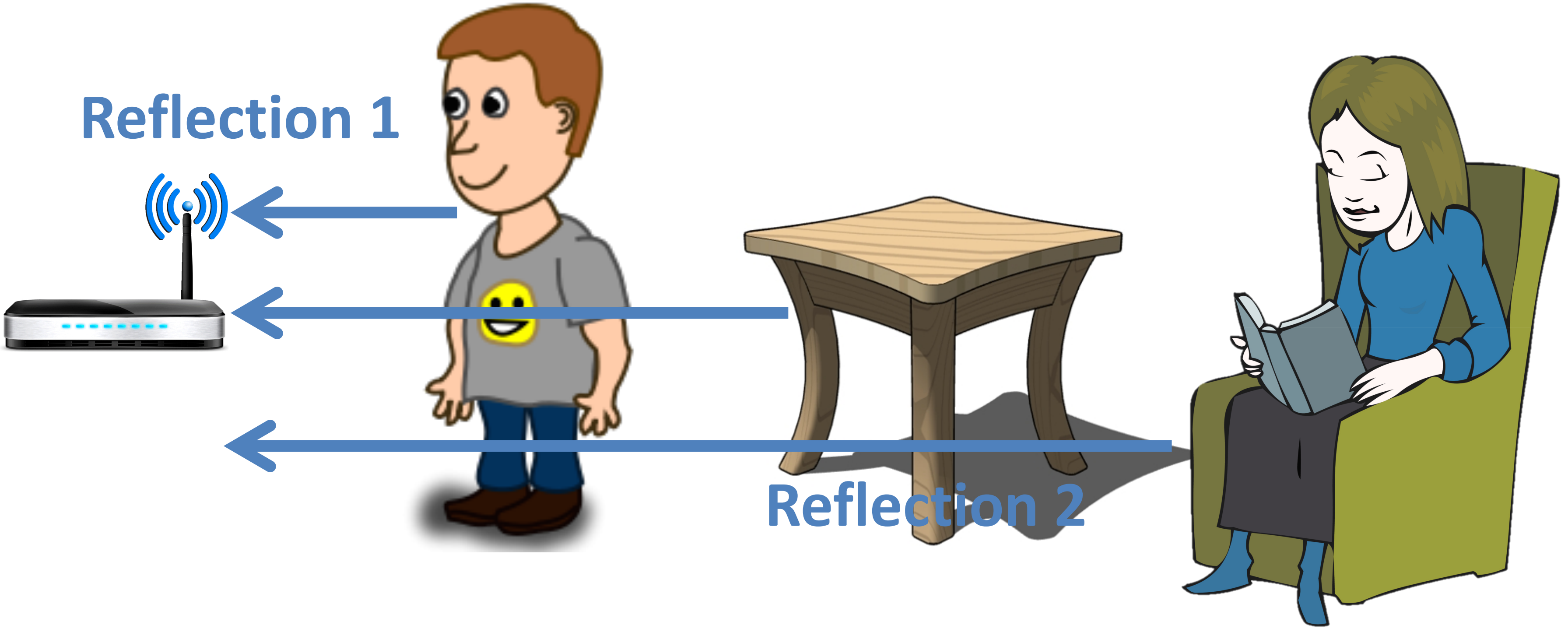
What happens with multiple users in the environment?

Reflections from different objects collide

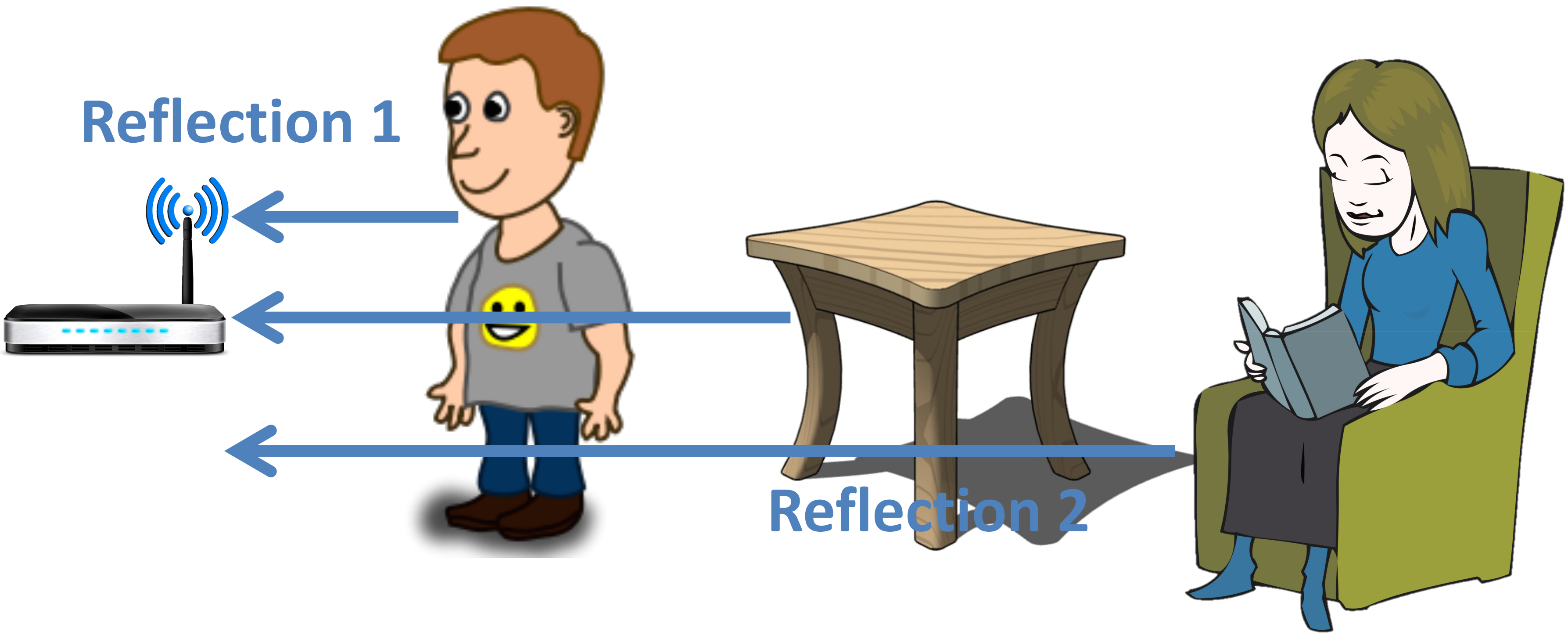
Problem: Phase becomes meaningless!



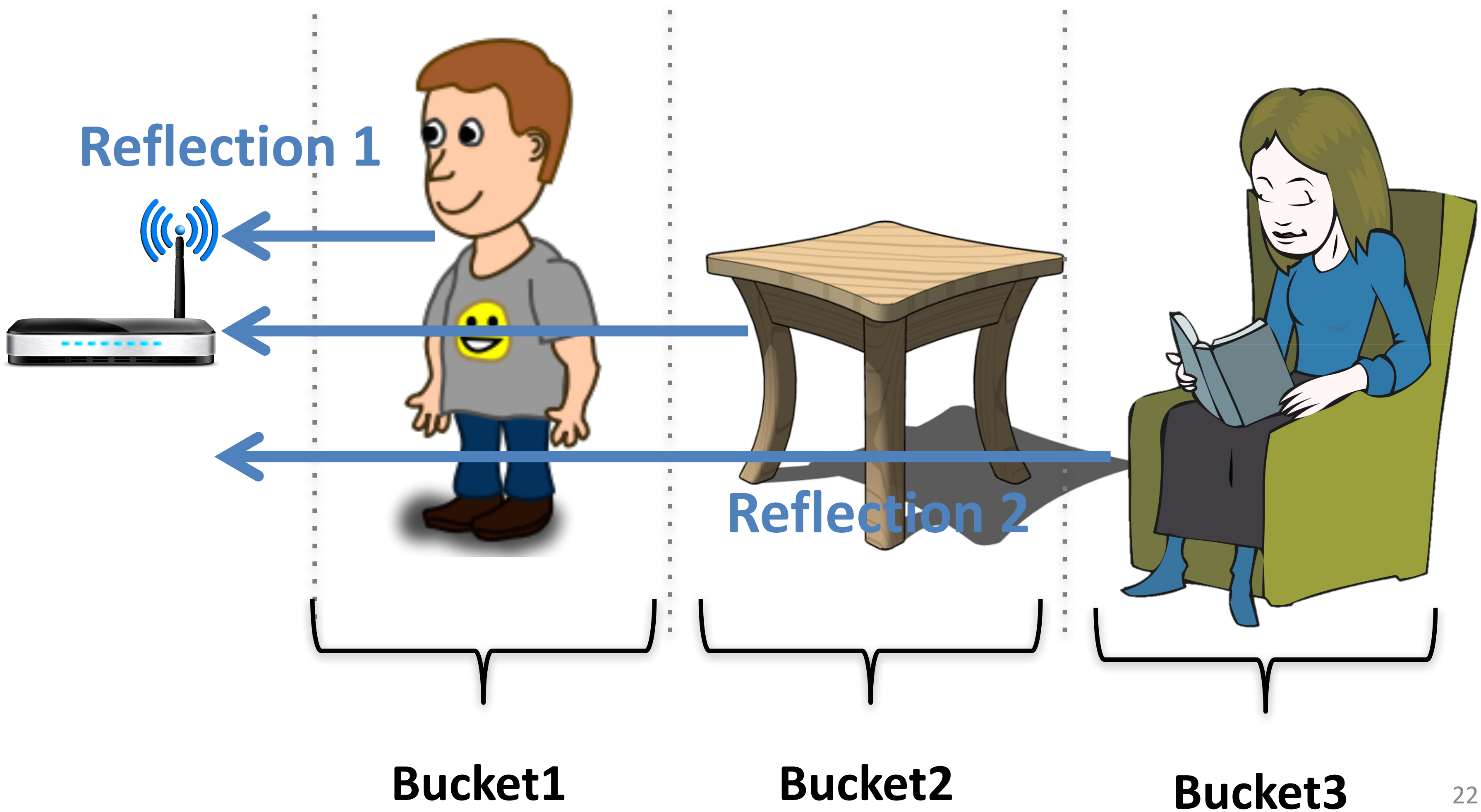
Idea: Wireless localization can be used to locate various devices



Solution: Use wireless localization as a filter to isolate reflections from different positions



Solution: Use wireless localization as a filter to isolate reflections from different positions



Putting It Together

Step 1: Transmit a wireless signal and capture its reflections

Step 2: Isolate reflections from different objects based on their positions

Step 3: Zoom in on each object's reflection to obtain phase variations due to vital signs

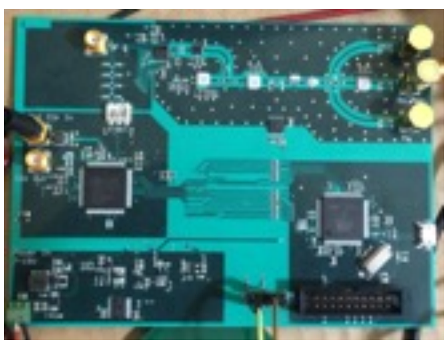
Through-wall breath monitoring of multiple users

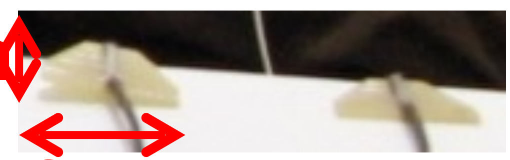
It captures chest motion using wireless signal reflections

Device is behind the wall

Vital-Radio Implementation

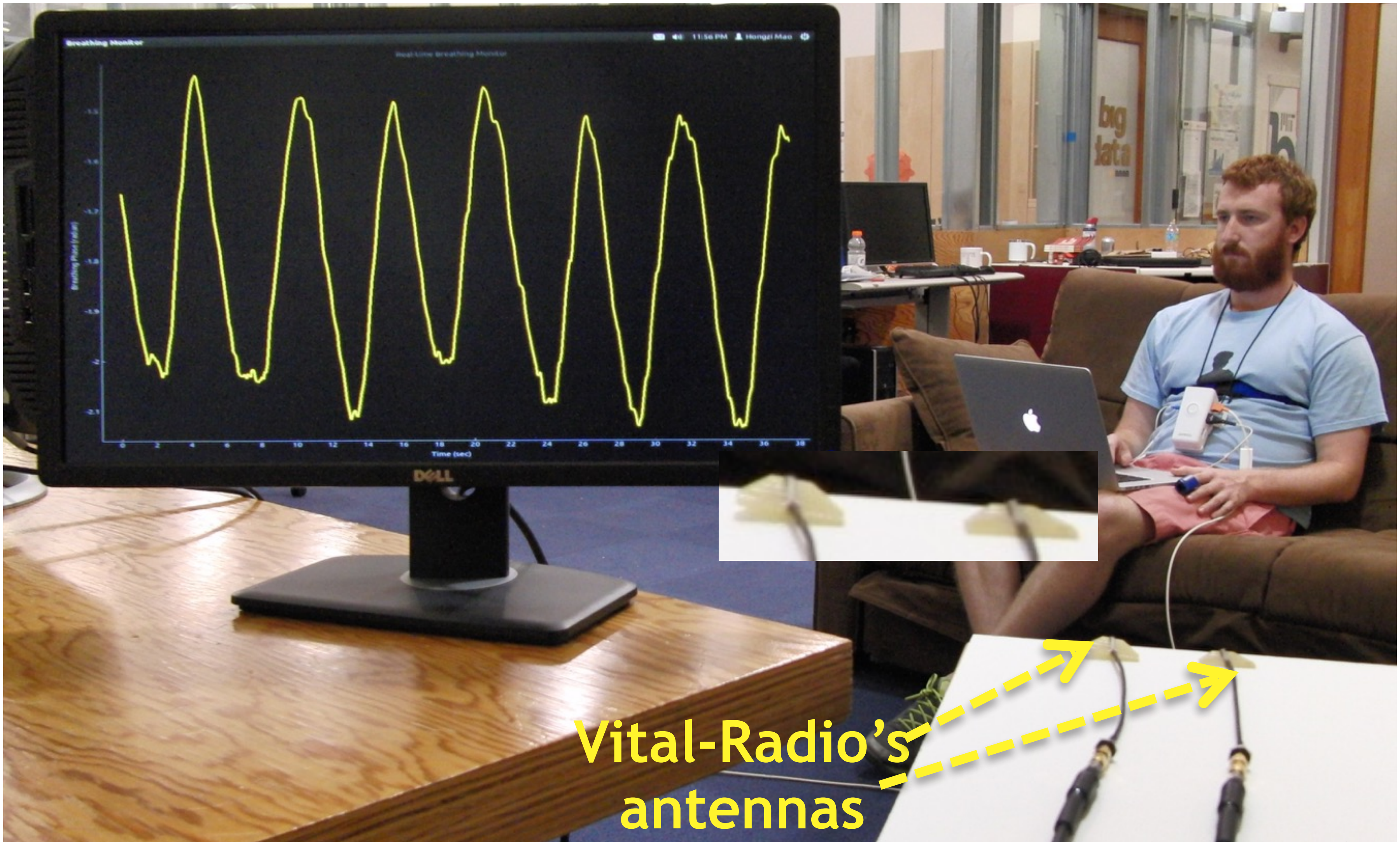
- Wireless positioning device to transmits and receives wireless signals
  - 10,000x lower power than cellphones
  - 1 transmit & 1 receive antenna





- Signal is analyzed in software to extract vital signs

Vital-Radio Implementation



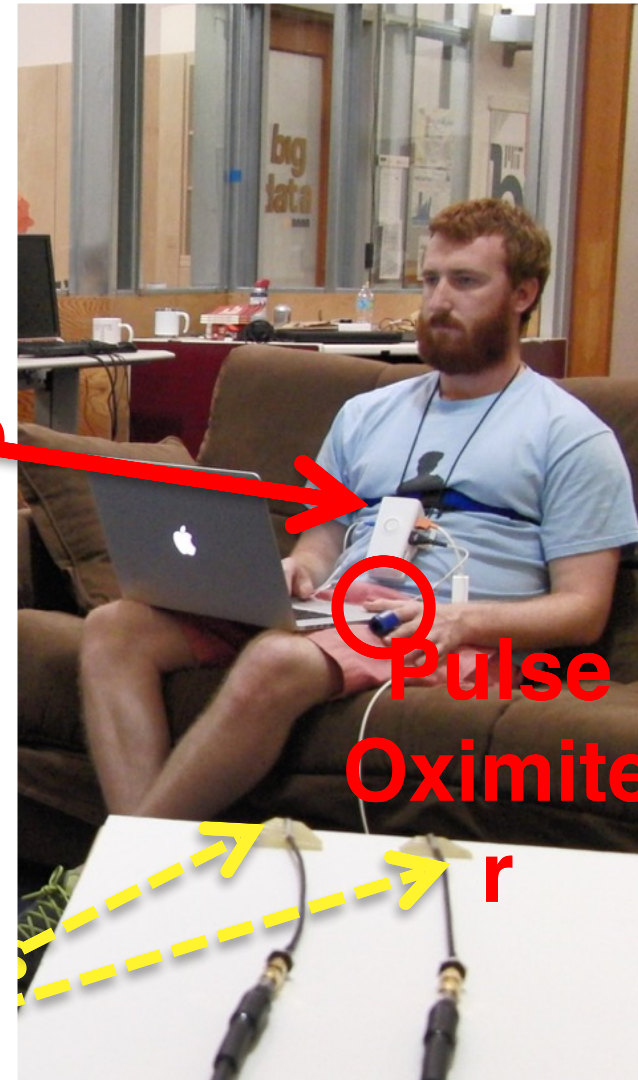
Vital-Radio Evaluation

Baseline:

- FDA-approved breathing and heart rate monitor

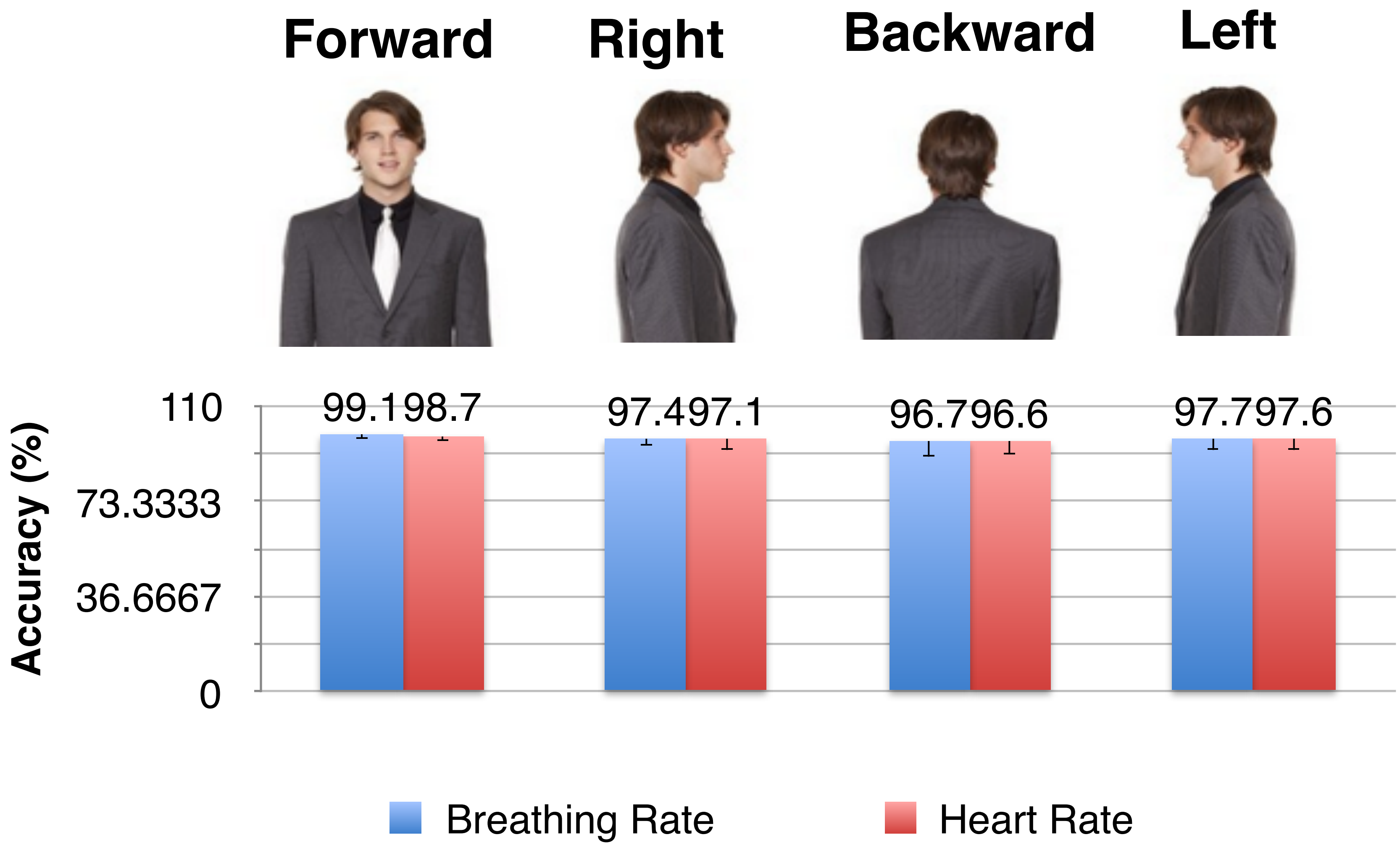
Experiments:

- 200 experiments
- 14 participants
- 1 million measurements



Accuracy vs. Orientation

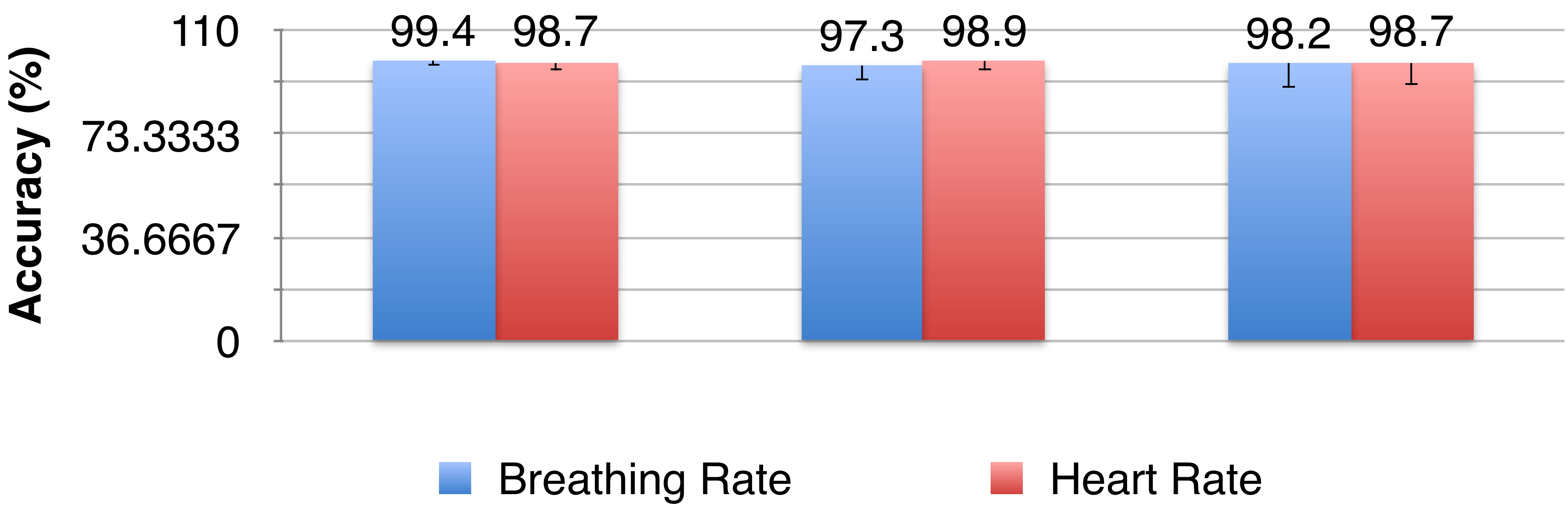
User is 4m from device, with different orientations



Accuracy for Multi-User Scenario

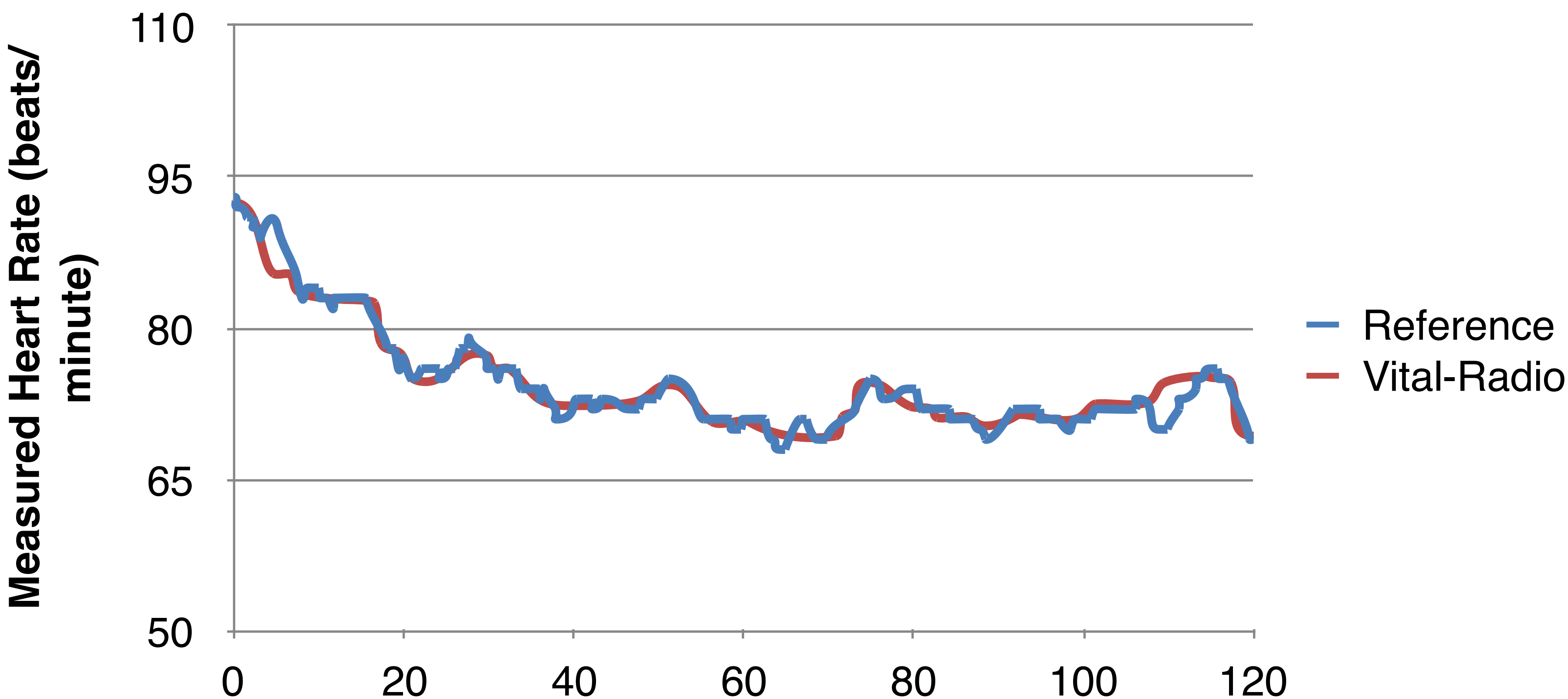
Multiple users sit at different distances

Nearest (at 2m) Middle (at 4m) Furthest (at 6m)



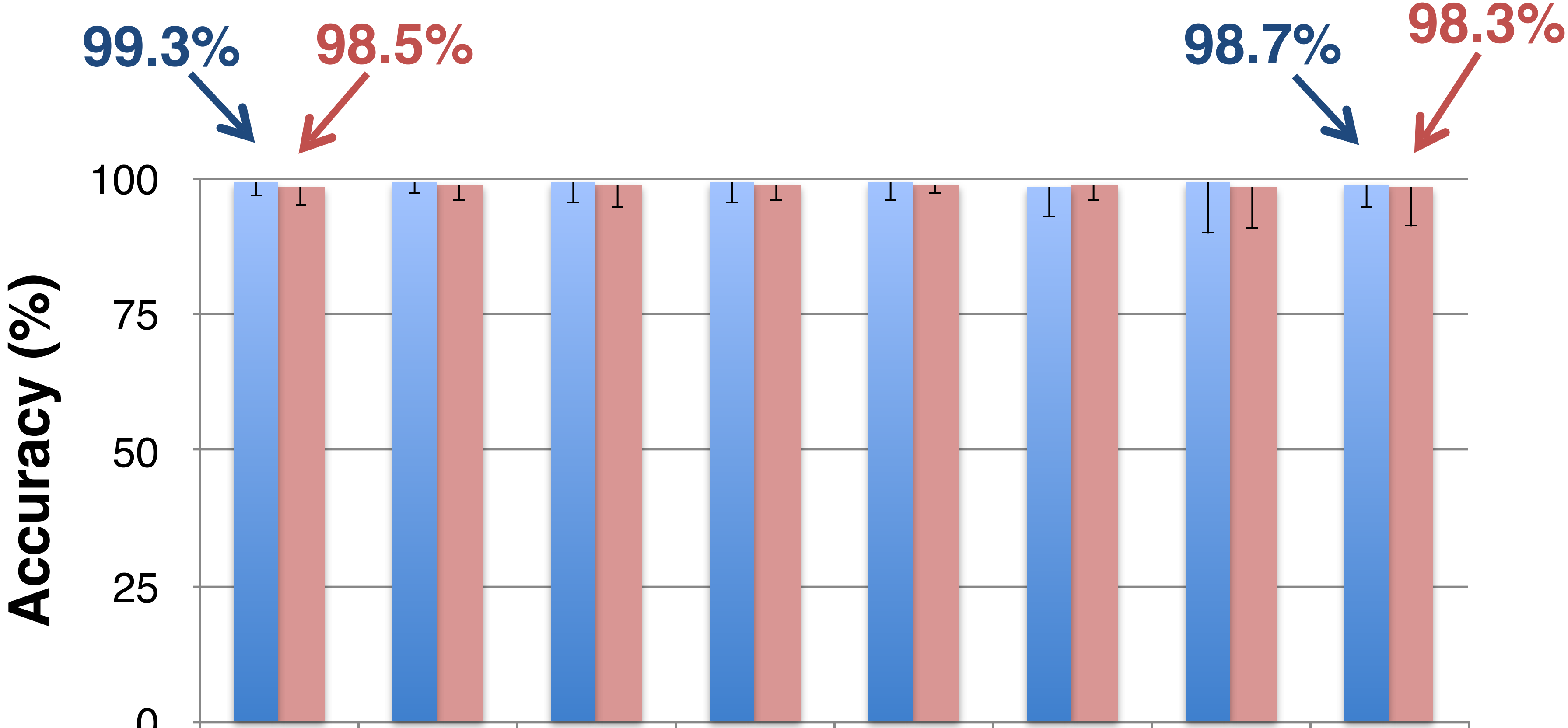
Accuracy for Tracking Heart Rate

Measure user's heart rate after exercising



Vital-Radio accurately tracks changes in vital signs

Accuracy versus Distance



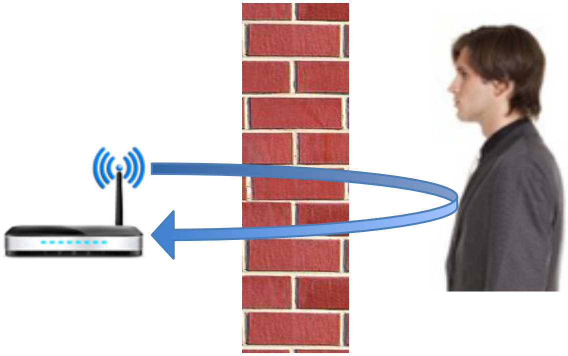
Breathing and Heart Rate Accuracy is ~99% in comparison to FDA-approved baseline

Accuracy for various cases

- User sits at 4m from device

  – Highest when facing (99%), lowest for back (96%)

- **<u>Through-Wall:</u>** User sits behind the wall (at 4m)



  – Breathing: **99.2%**
  – Heart Rate: **90.1%**

Accuracy for various cases

- **<u>Multi-User:</u>** Users sit at different distances

Nearest: **99.1%** Middle: **98.1%** Furthest: **98.4%**

- **<u>Daily Activities:</u>**

Smartphone: **99.2%**

Laptop: **99%**

Vital-Radio Limitations

- Minimum separation between users: 1-2m
- Monitoring range: 8m
- Collects measurements when users are quasi-static

Baby Monitoring