MAS.S61: Emerging Wireless & Mobile Technologies
aka The “Extreme IoT” Class

Lecture 3:
Fundamentals of Wireless Sensing & Localization (Con’t)
Fundamentals of Communications & Connectivity

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Website: http://www.mit.edu/~fadel/courses/MAS.S61/index.html

Logistics & Norm Settings

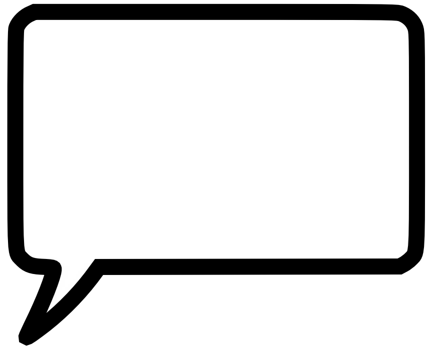
- What to do now?
  1. Turn on your video (if your connection allows it)
  2. Mute your mic (unless you are the active speaker)
  3. Open the “Participant” List
     - Make sure your full name is shown

On

Mute

- If you have a question:
  - Use the chat feature to either write the question or to indicate your interest in asking the question
  - We will be monitoring the chat
  - Unmute -> ask question -> mute again
  - Once done asking/answering, please state “Done” to clearly mark it (helps translation/moderation)
  - Same procedure for answering questions

Chat



- This lecture will be recorded. It will only be accessible to people in the class

REC

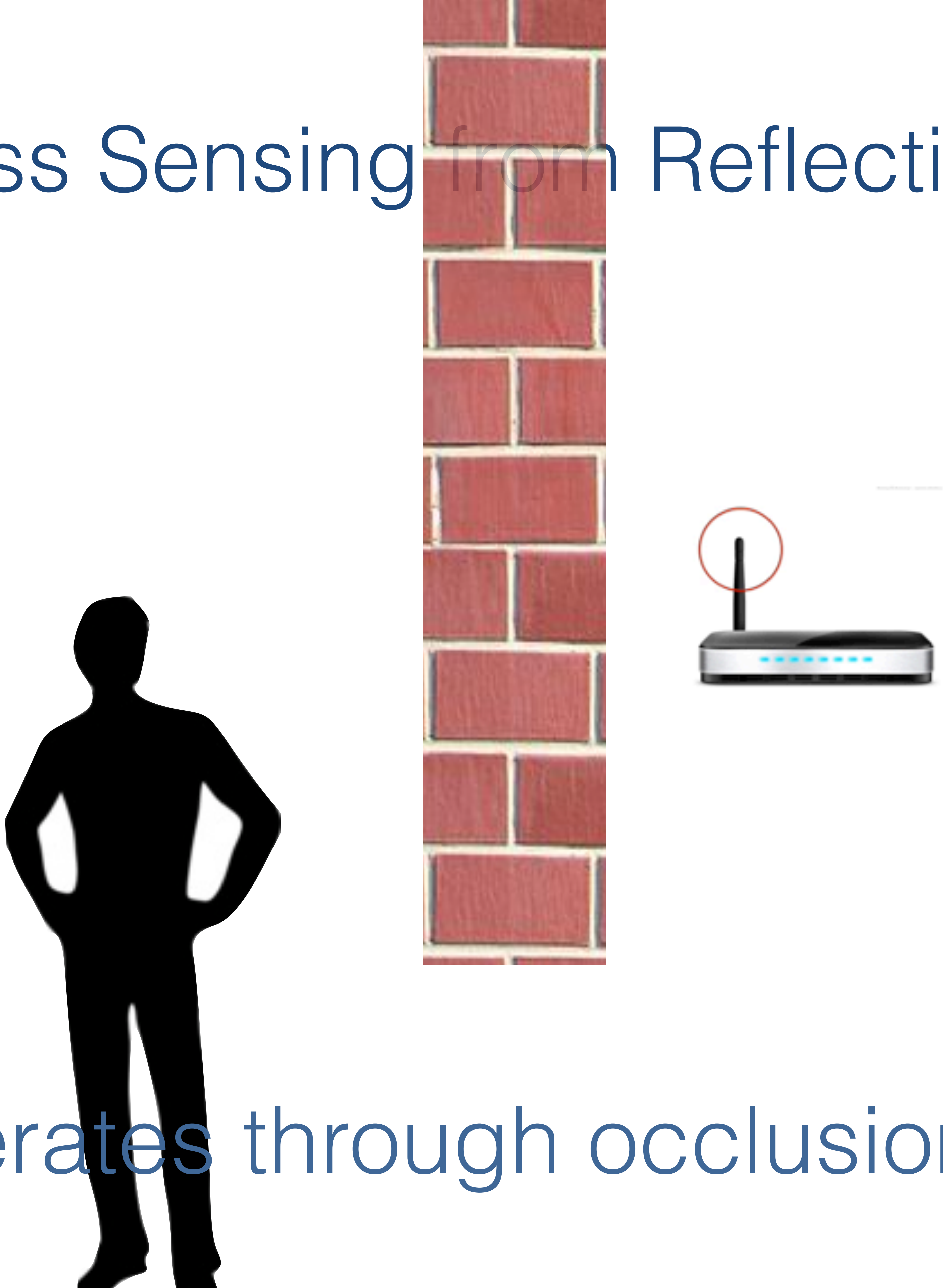
Objectives of Today's Lecture

1. Learning the fundamentals of wireless (aka WiFi) sensing and its current industry trends
2. Learning the fundamentals of end-to-end wireless communications:
   - The physical, mathematical, engineering, and design fundamentals
     - "Why are these systems designed the way they are"
   - Case study of a new wireless communication system (underwater-to-air comms)

Recap: Localization Approaches

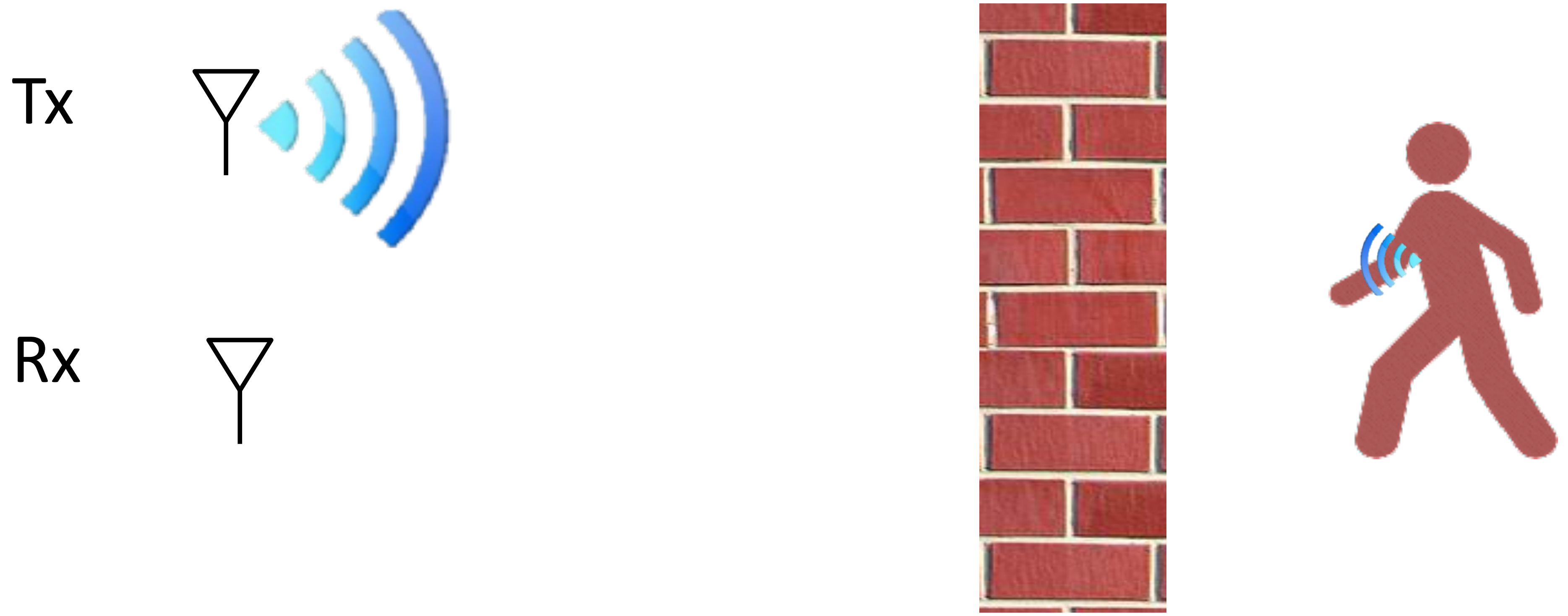
1. Identify-based
2. RSSI-based (including fingerprinting)
3. Phase-based
4. AoA+Triangulation
5. ToF+Trilateration
6. DToA

Wireless Sensing from Reflections



Operates through occlusions

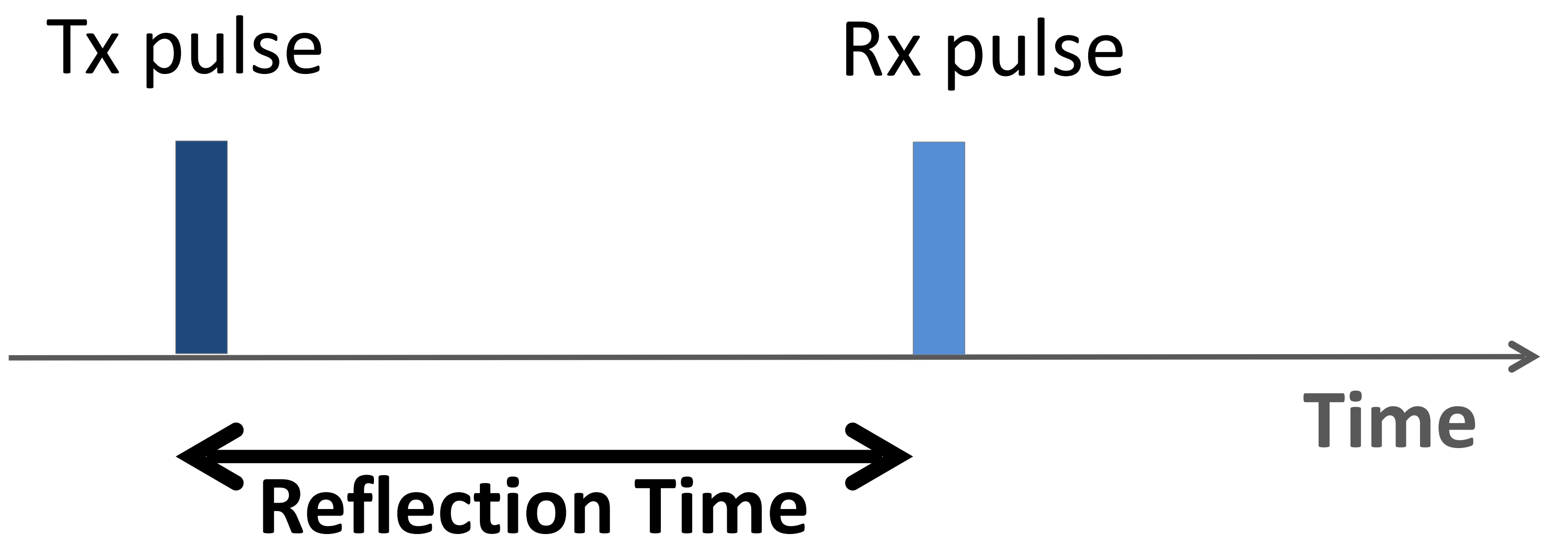
Measuring Distances



Distance = Reflection time x speed of light

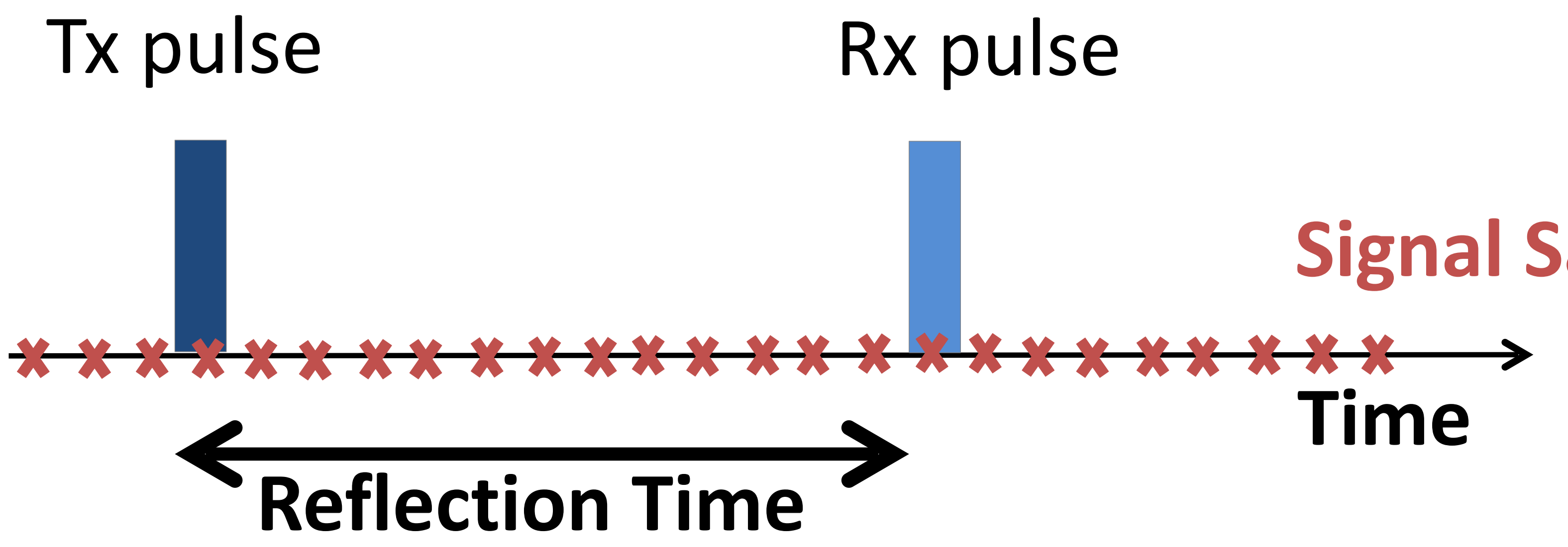
Measuring Reflection Time

Option1: Transmit short pulse and listen for echo



Measuring Reflection Time

<u>Option1:</u> Transmit short pulse and listen for echo

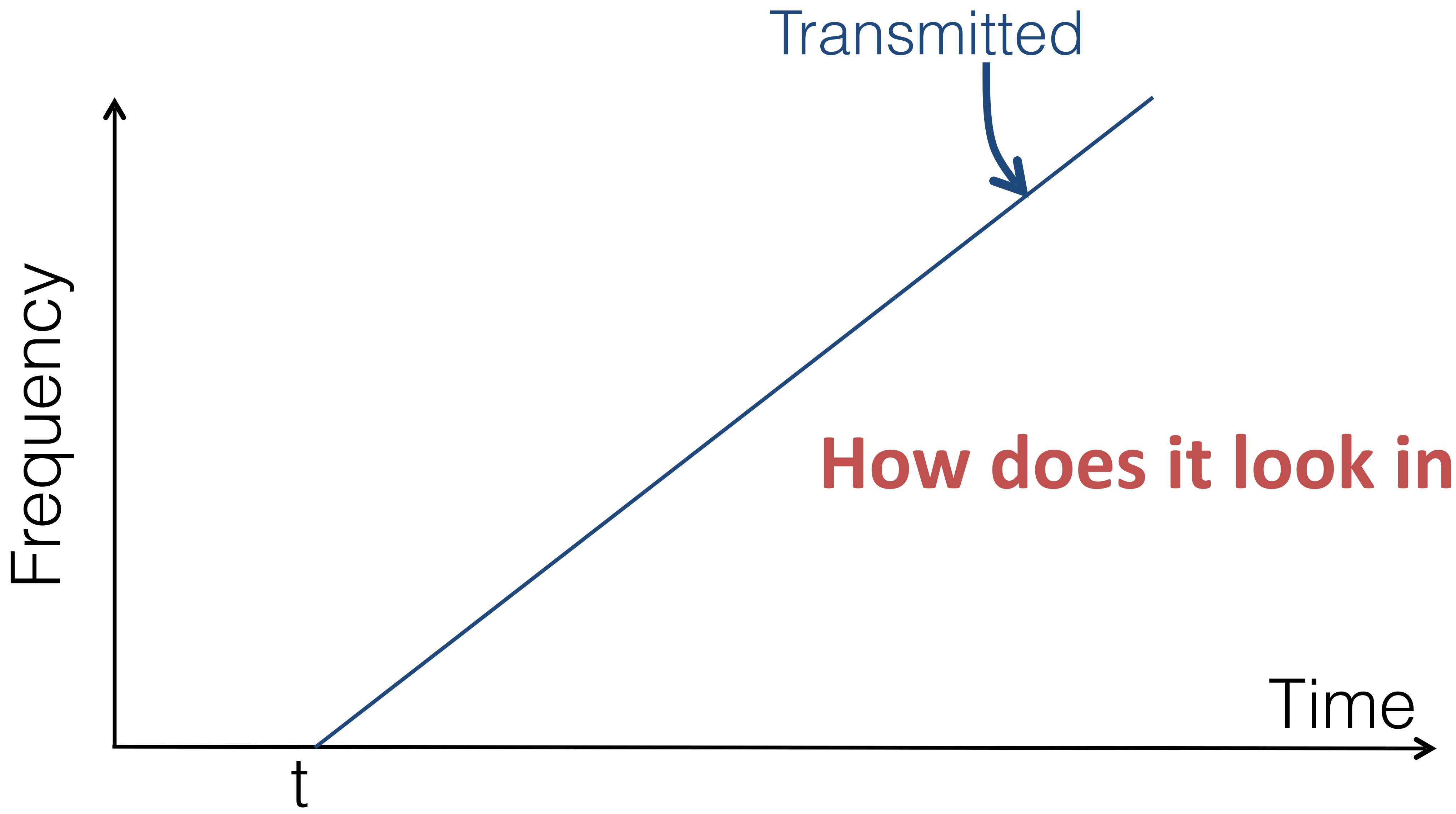


Capturing the pulse needs sub-nanosecond sampling

Why?

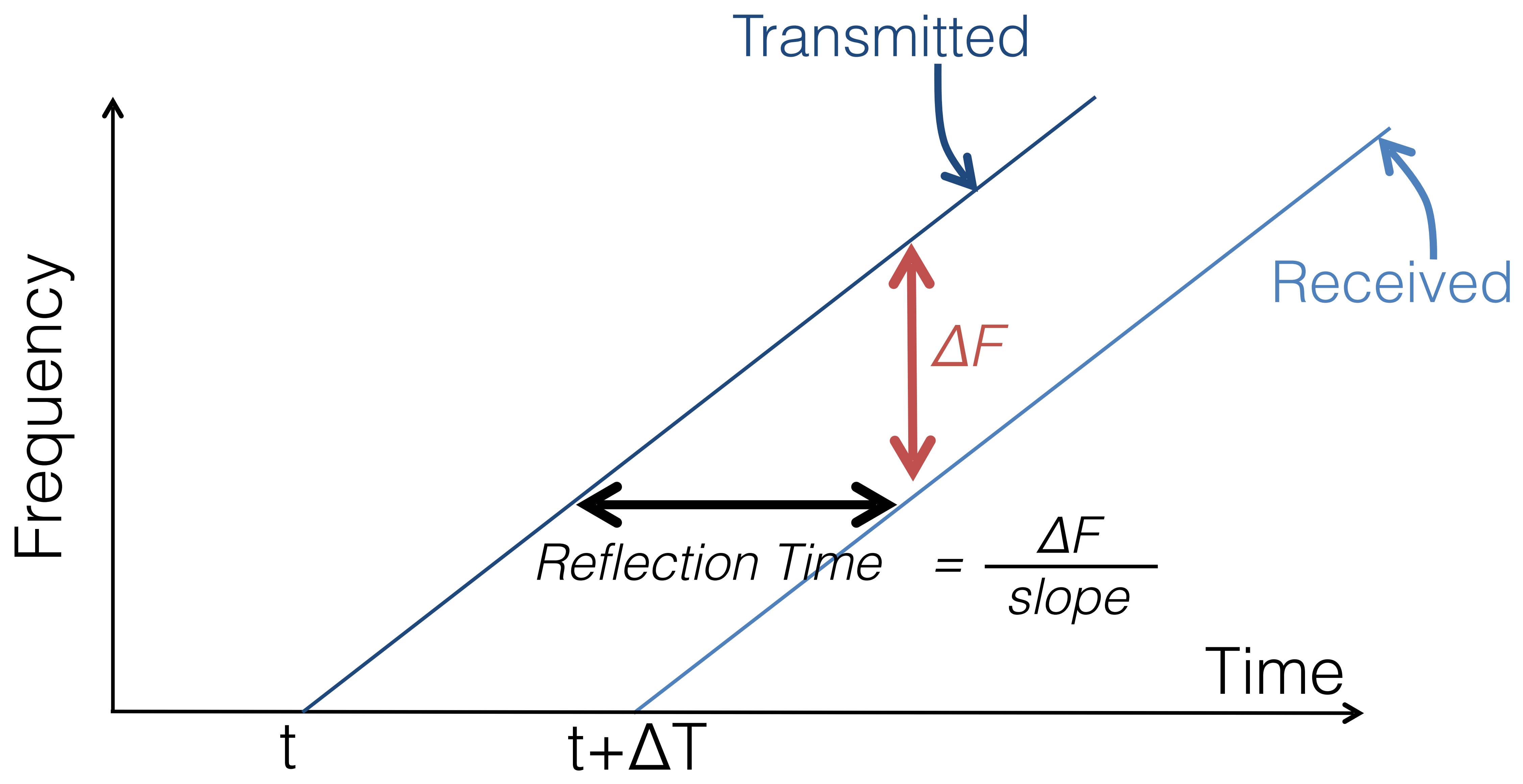
Would it also be a problem for acoustic or ultrasound-based methods?

FMCW: Measure time by measuring frequency



How does it look in time domain?

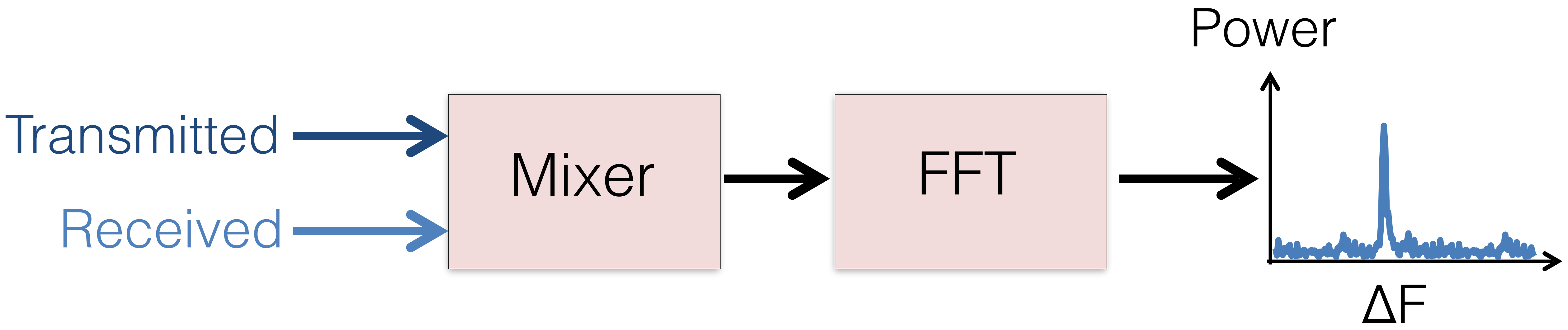
FMCW: Measure time by measuring frequency



How do we measure ΔF?

Measuring ΔF

- Subtracting frequencies is easy (e.g., removing carrier in WiFi)
- Done using a mixer (low-power; cheap)



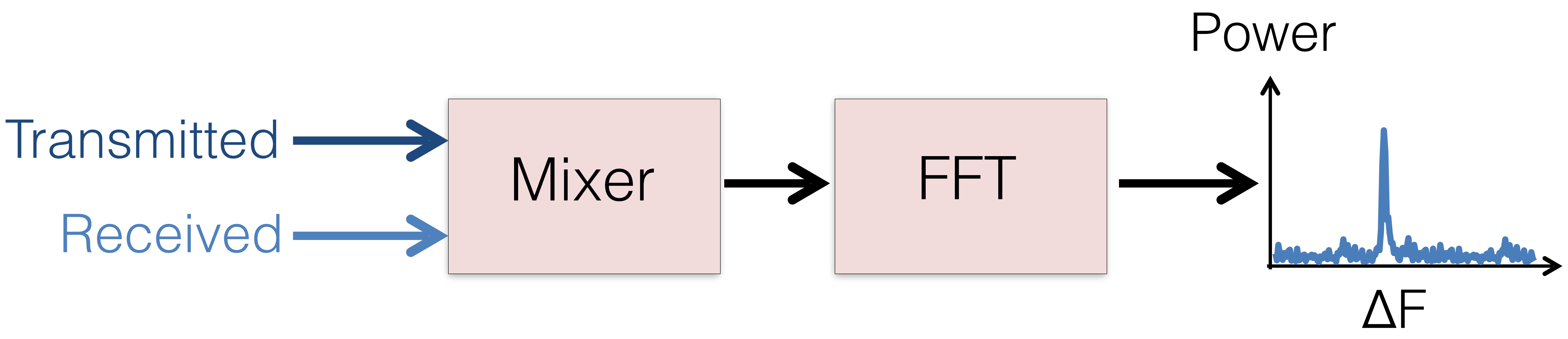
Signal whose frequency is ΔF

let's talk about FFTs a bit — freq

Basics of Fourier Transform

Measuring ΔF

- Subtracting frequencies is easy (e.g., removing carrier in WiFi)
- Done using a mixer (low-power; cheap)

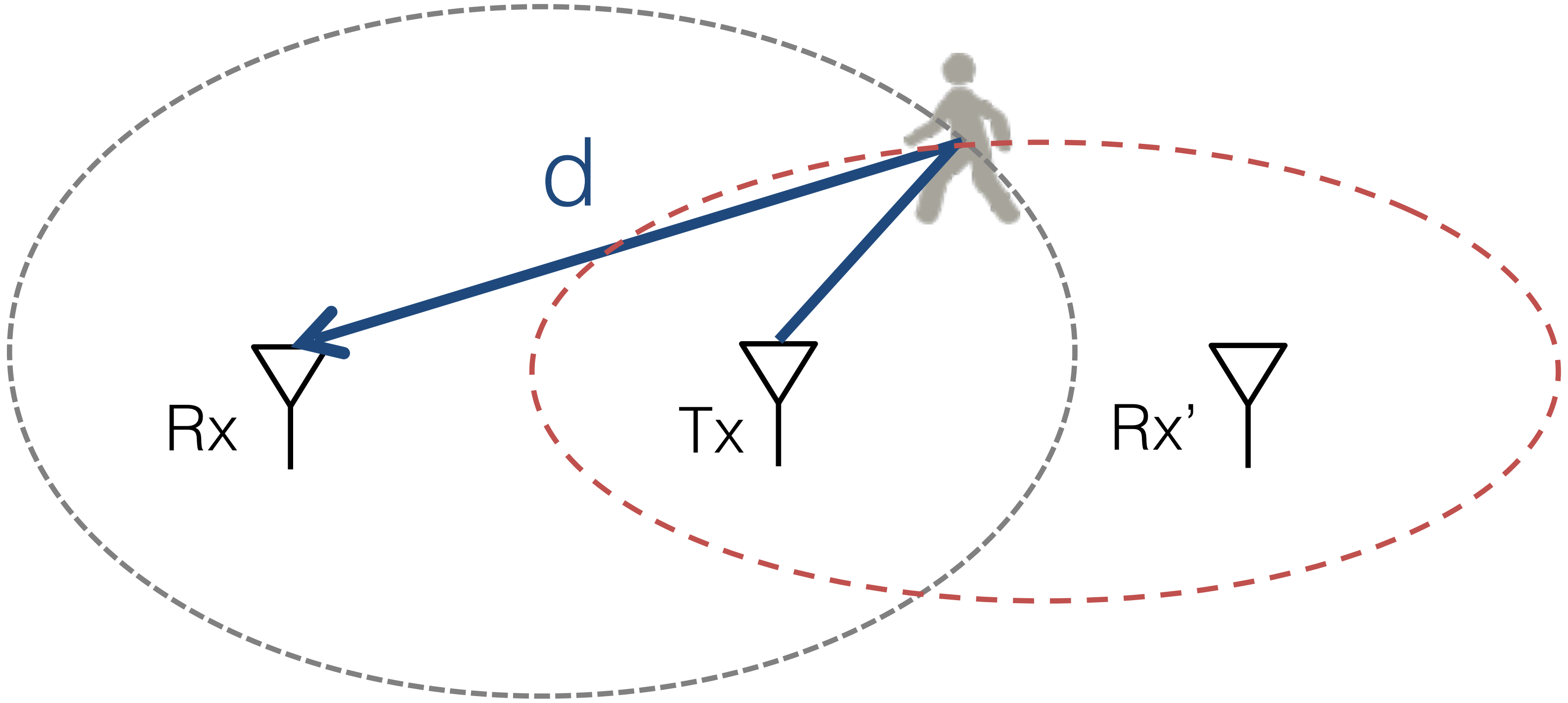


Signal whose frequency is ΔF

ΔF → Reflection Time → Distance

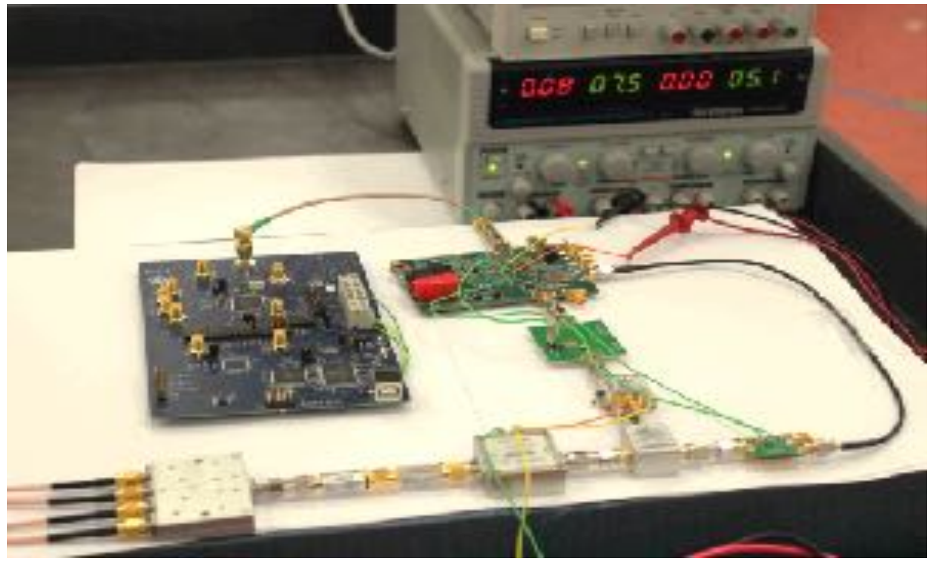
Mapping Distance to Location

Person can be anywhere on an ellipse whose foci are (Tx,Rx)



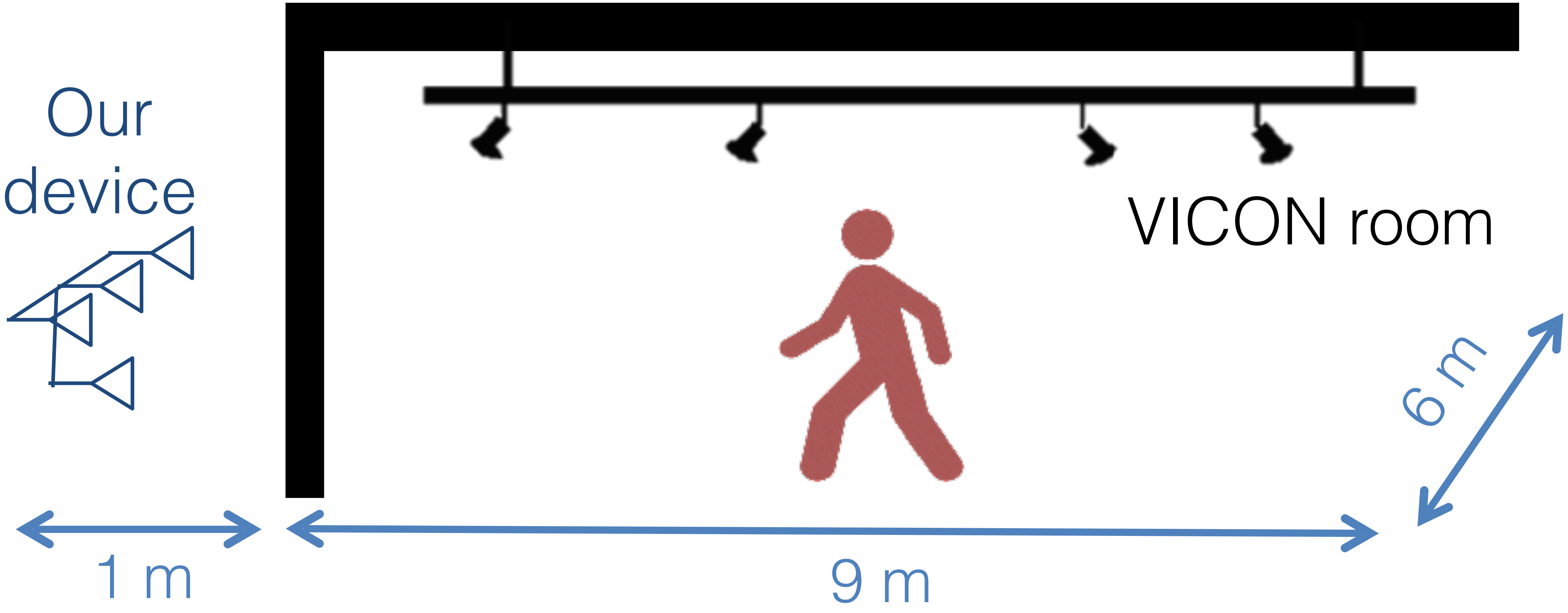
By adding another antenna and intersecting the ellipses, we can localize the person

Implementation



- Built FMCW front-end
  - Connected to USRP
- Band: 5.5-7.2 GHz
- Transmit 70 μW
  - 1000x lower power than WiFi Access Point

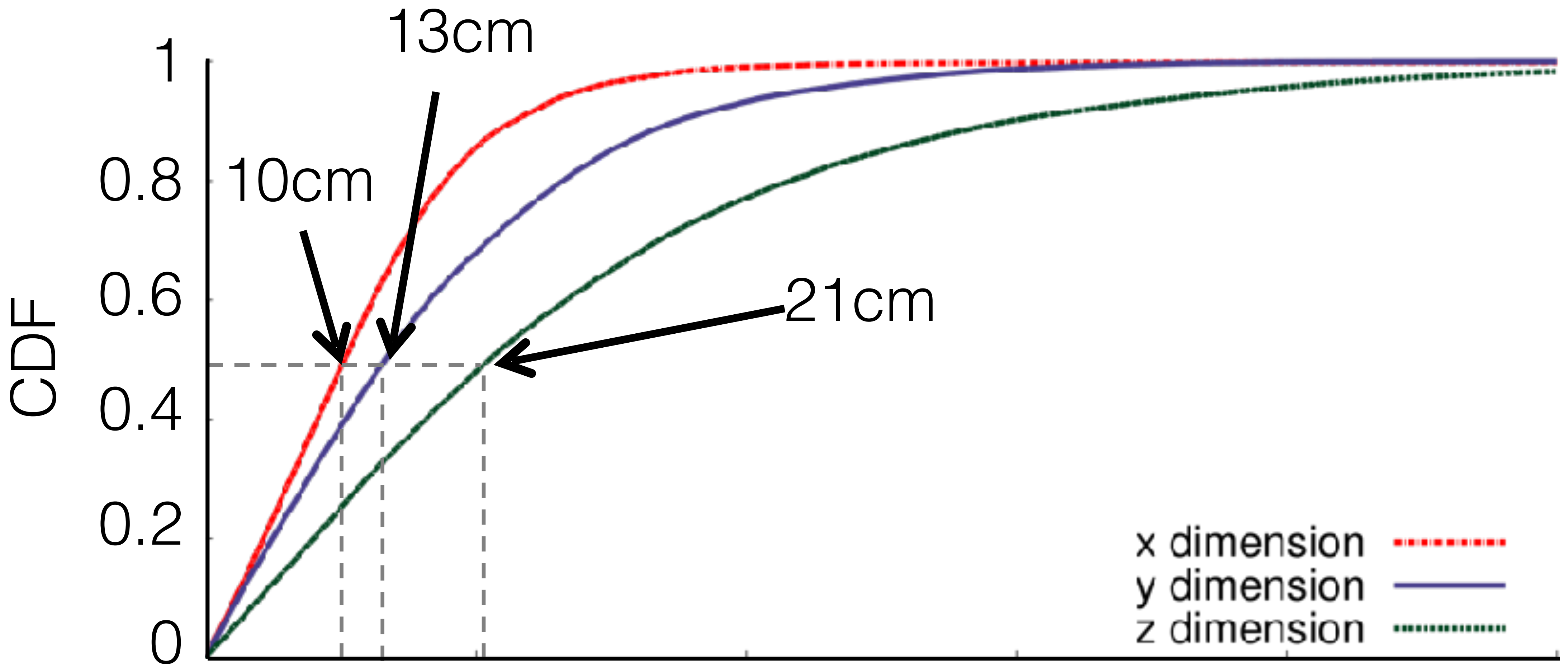
Ground Truth via VICON



- VICON uses an array of infrared cameras on the ceiling and operates in line-of sight
  - It achieves sub-cm-scale accuracy
- Our device is placed outside the room

Through-Wall Localization Accuracy

100 experiments: ½ million location measurements

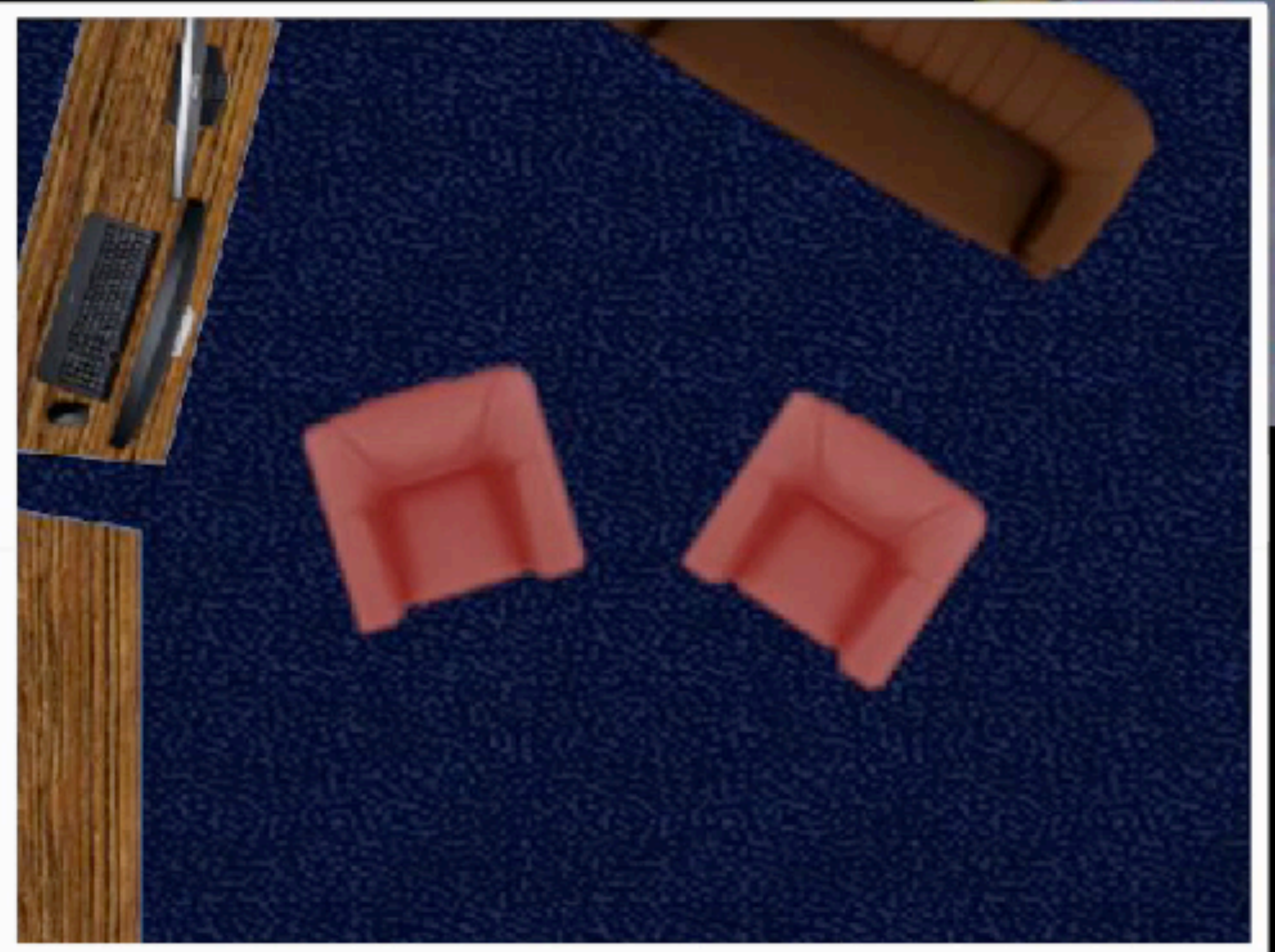


Centimeter-scale localization without requiring the user to carry a wireless device

What are some problems with WiTrack?

How would you improve it?

Societal implications

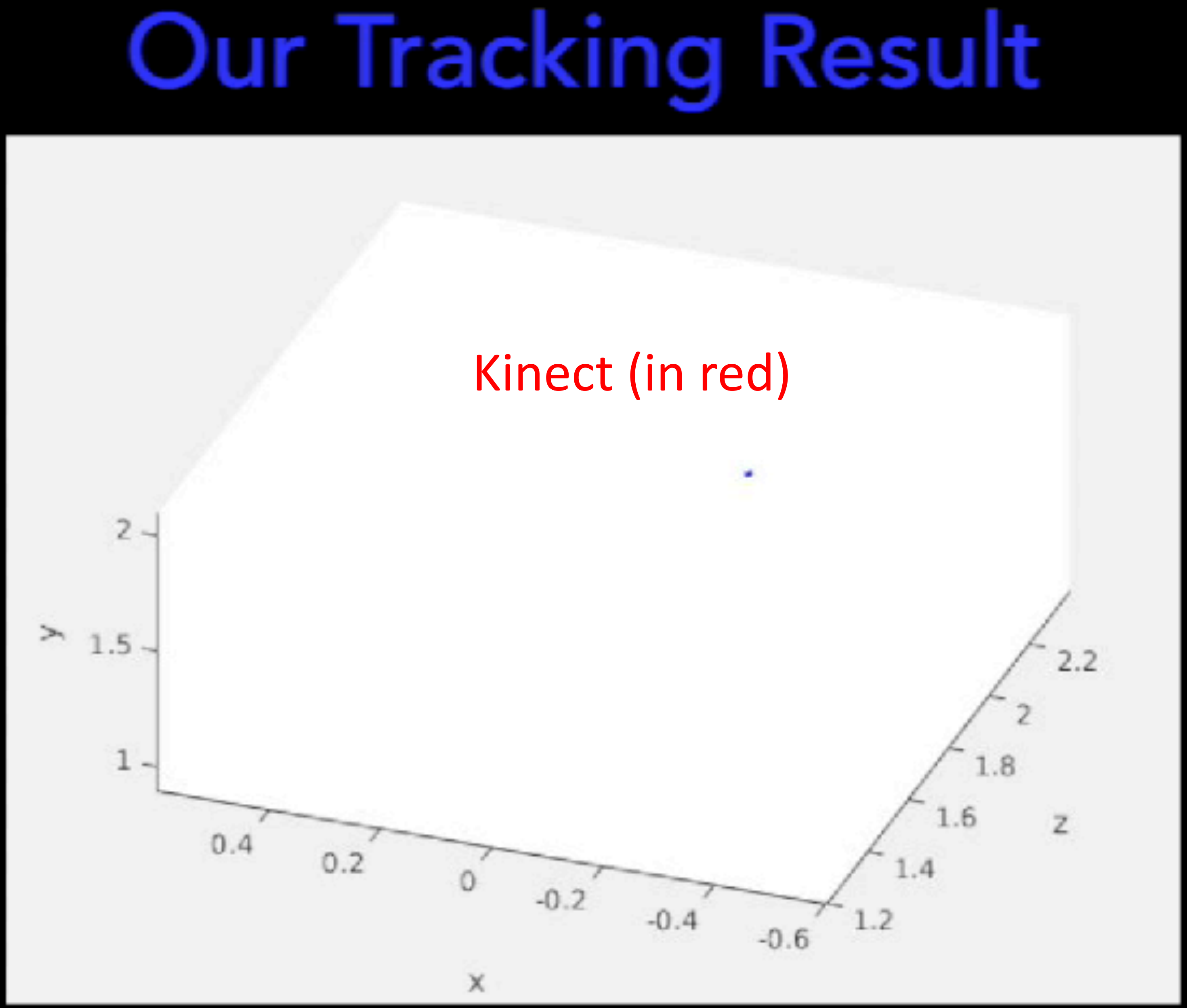




COMMUNICATIONS
ACM

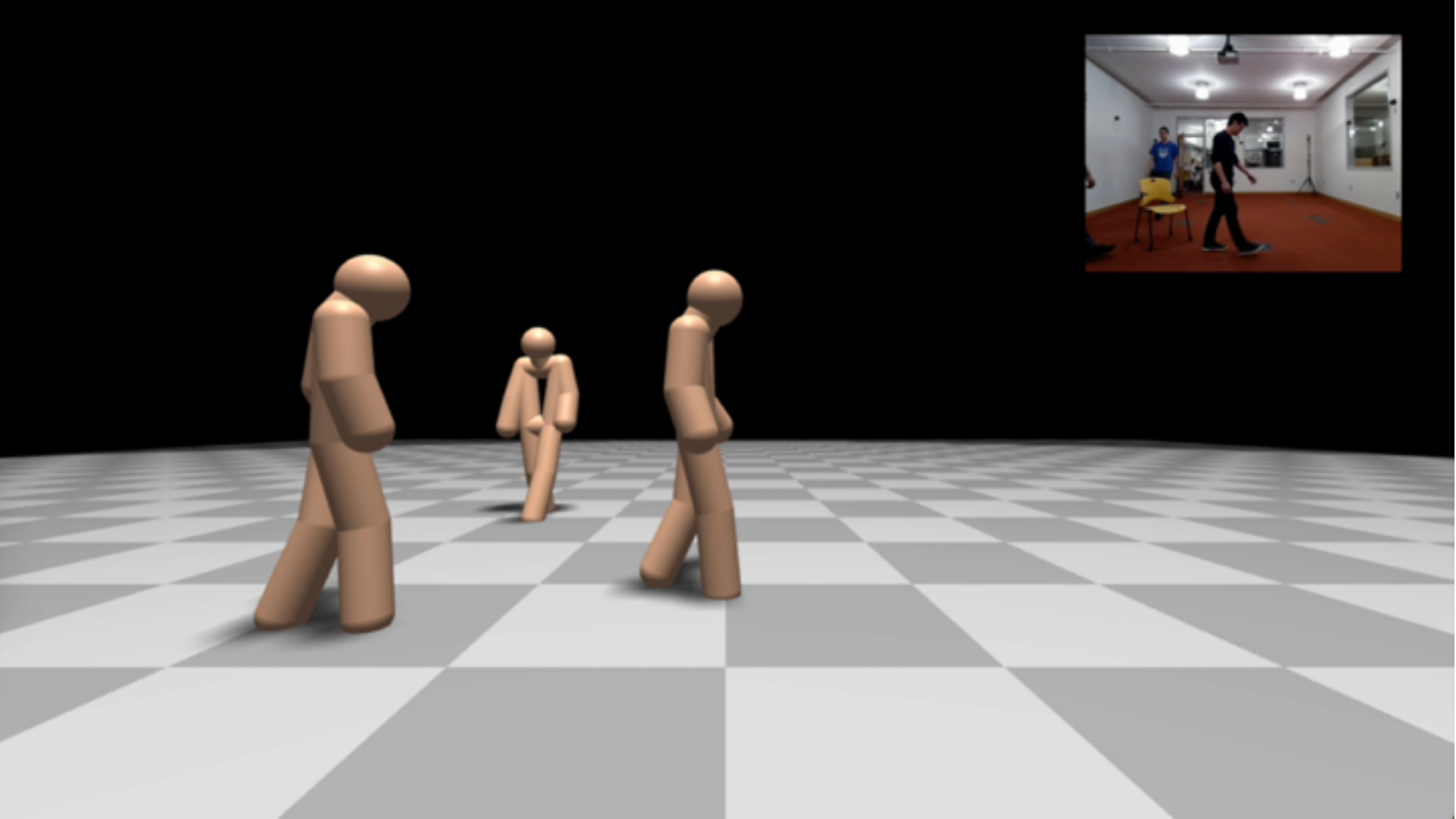
Who is behind the wall?

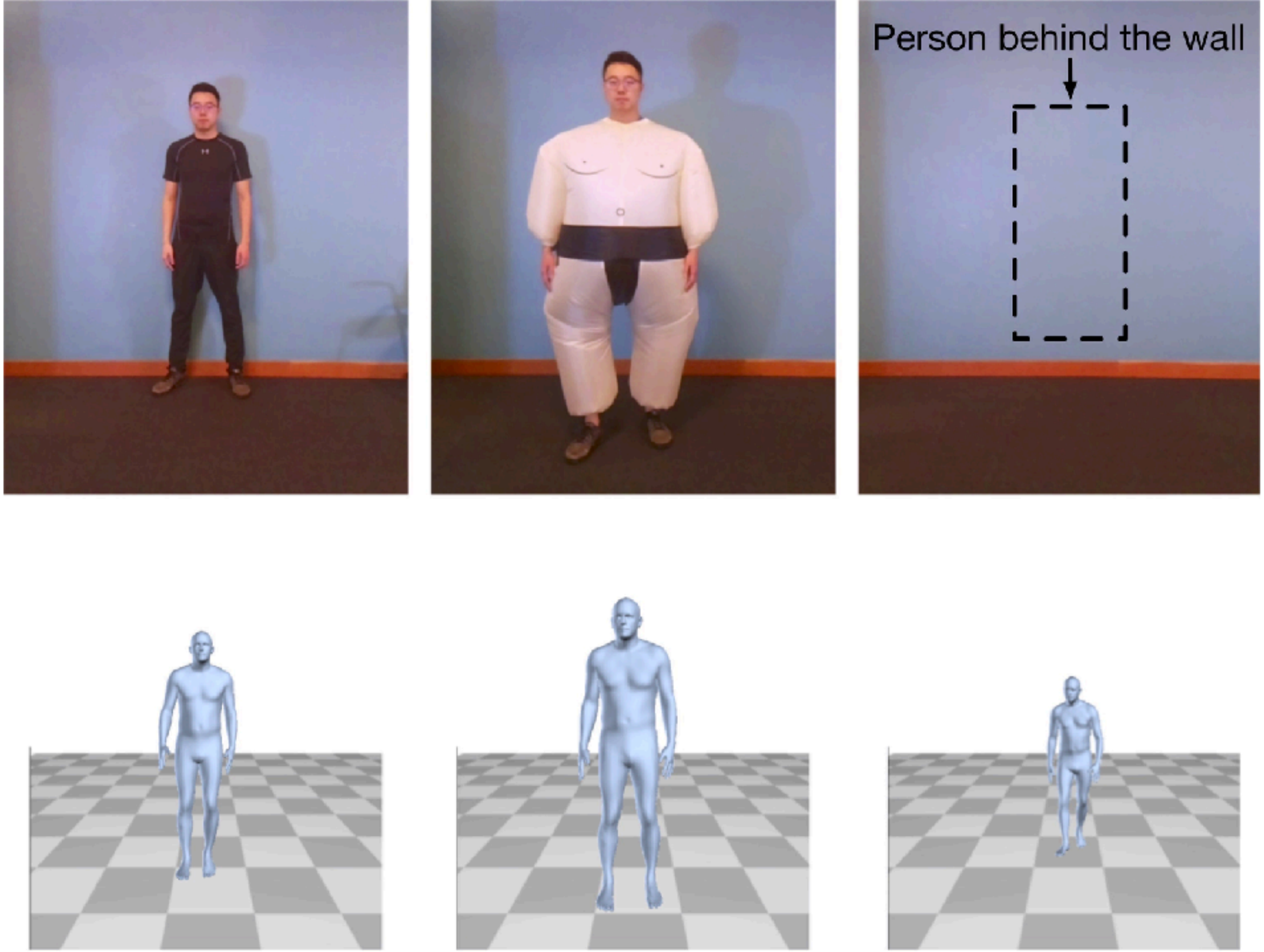
How is the person standing?

Writing in the air



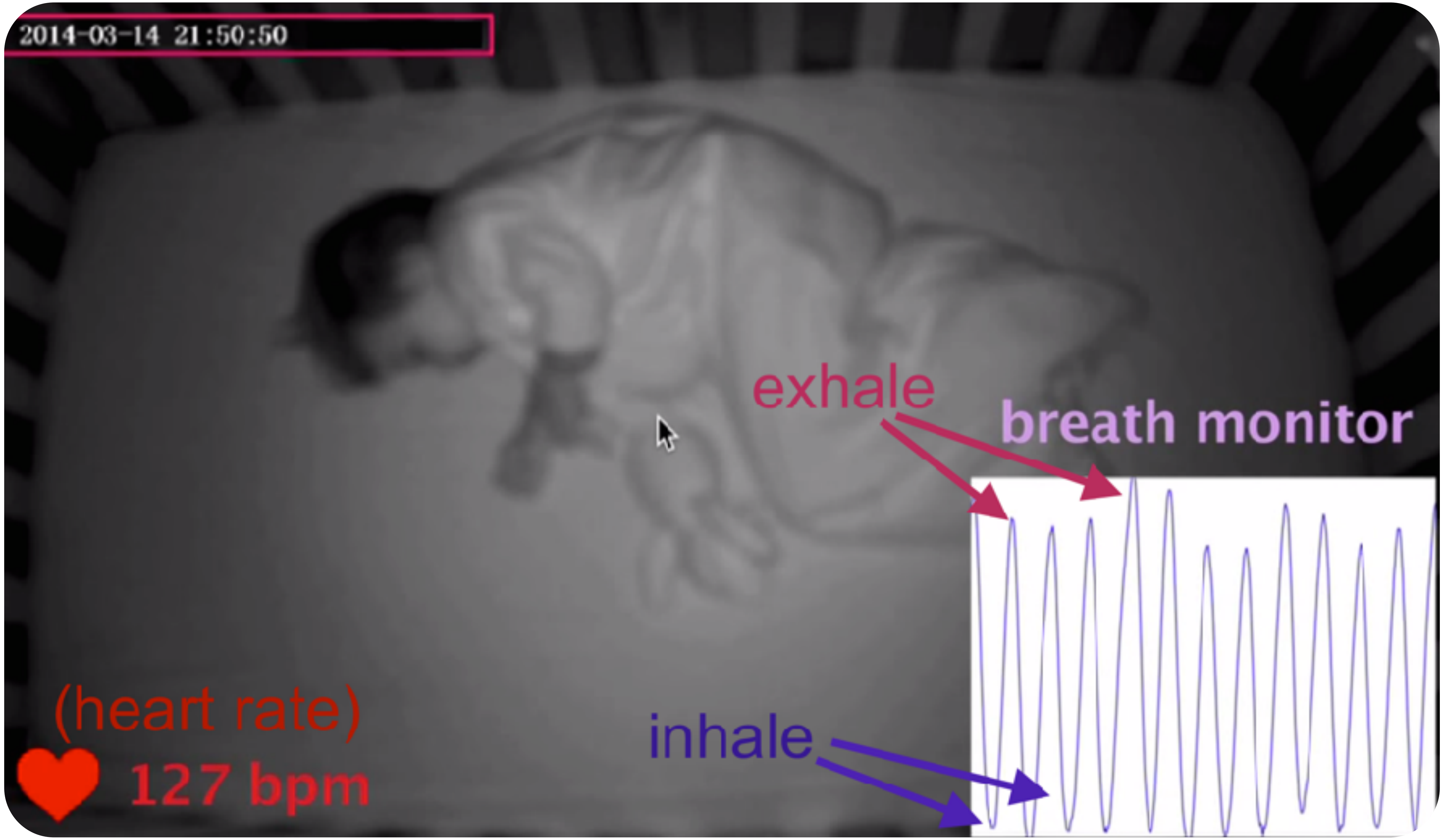

AI Senses People Through Walls




Person behind the wall

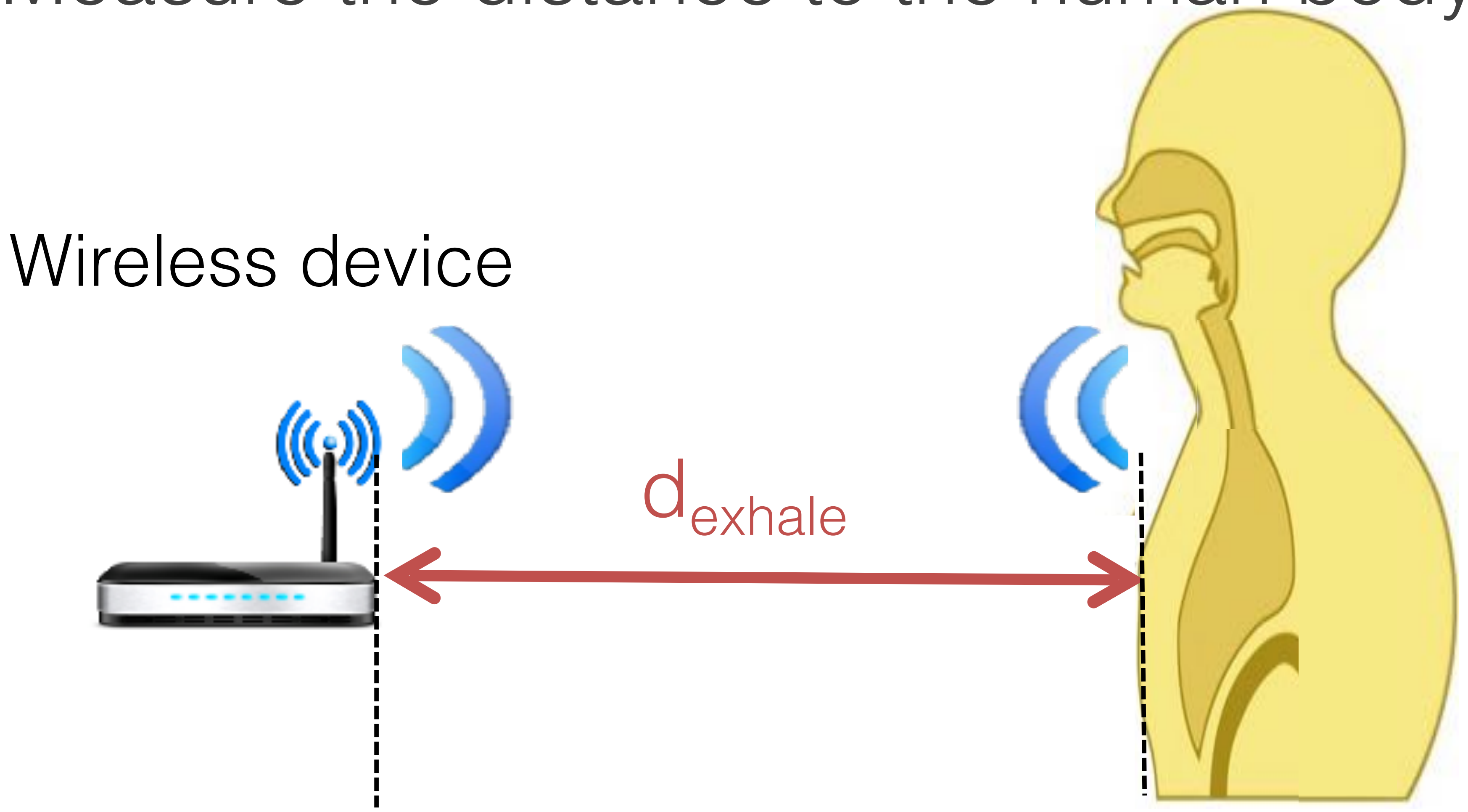
Remotely Measuring Breathing and HR

[CHI'15]

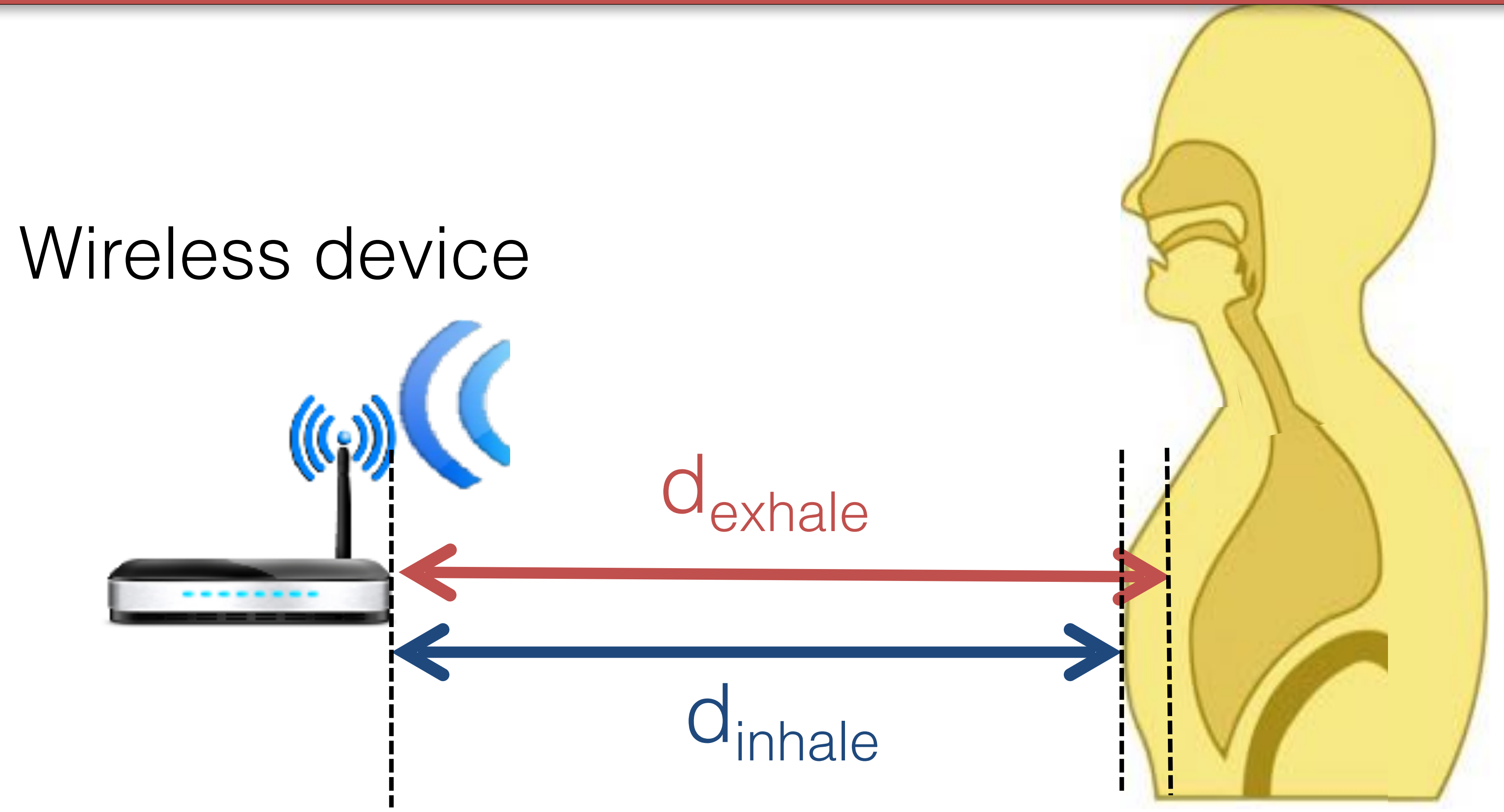


Idea: Use wireless reflections off the human body

Measure the distance to the human body

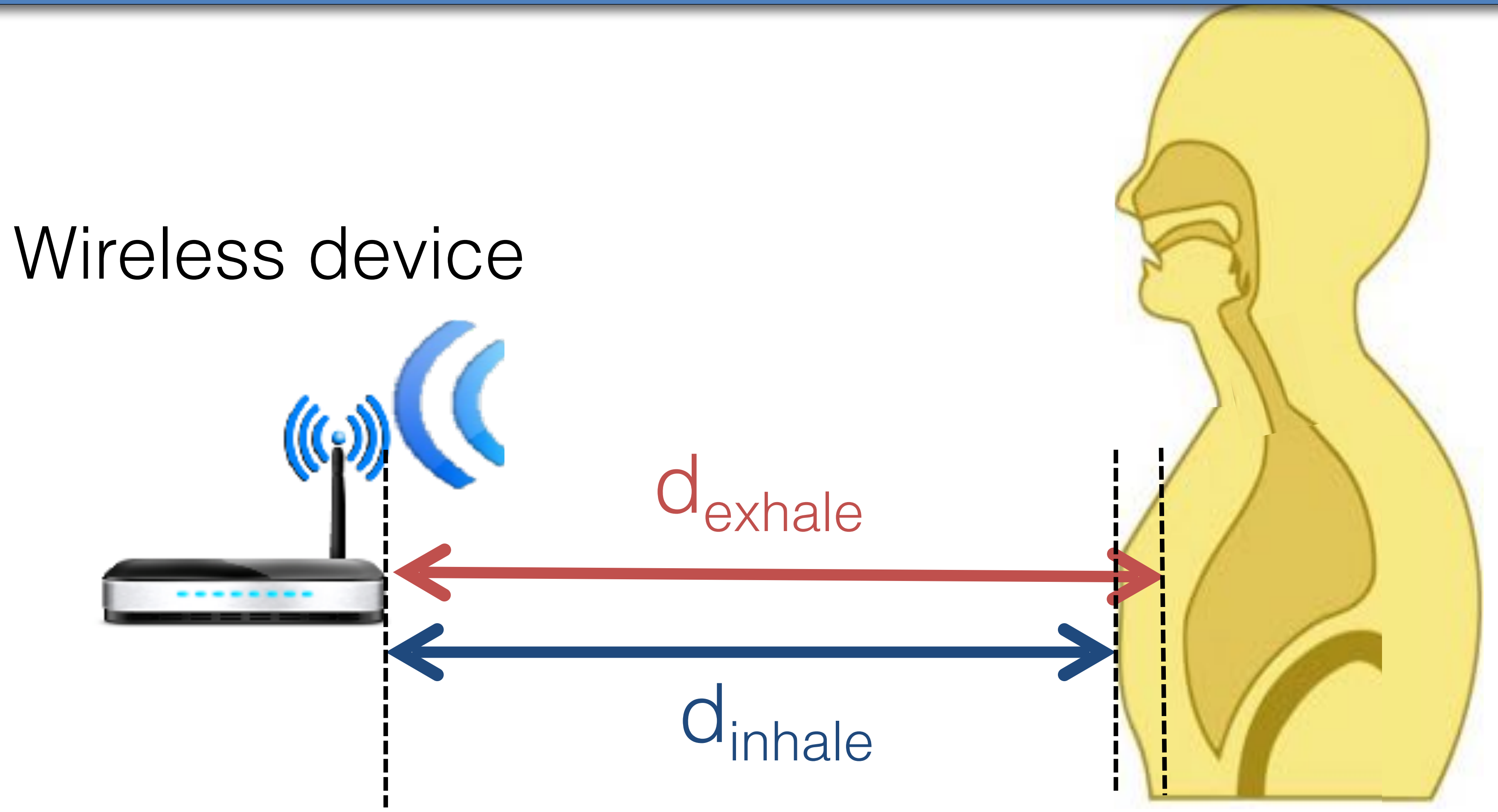


Problem: Localization accuracy is only 12cm and cannot capture vital signs



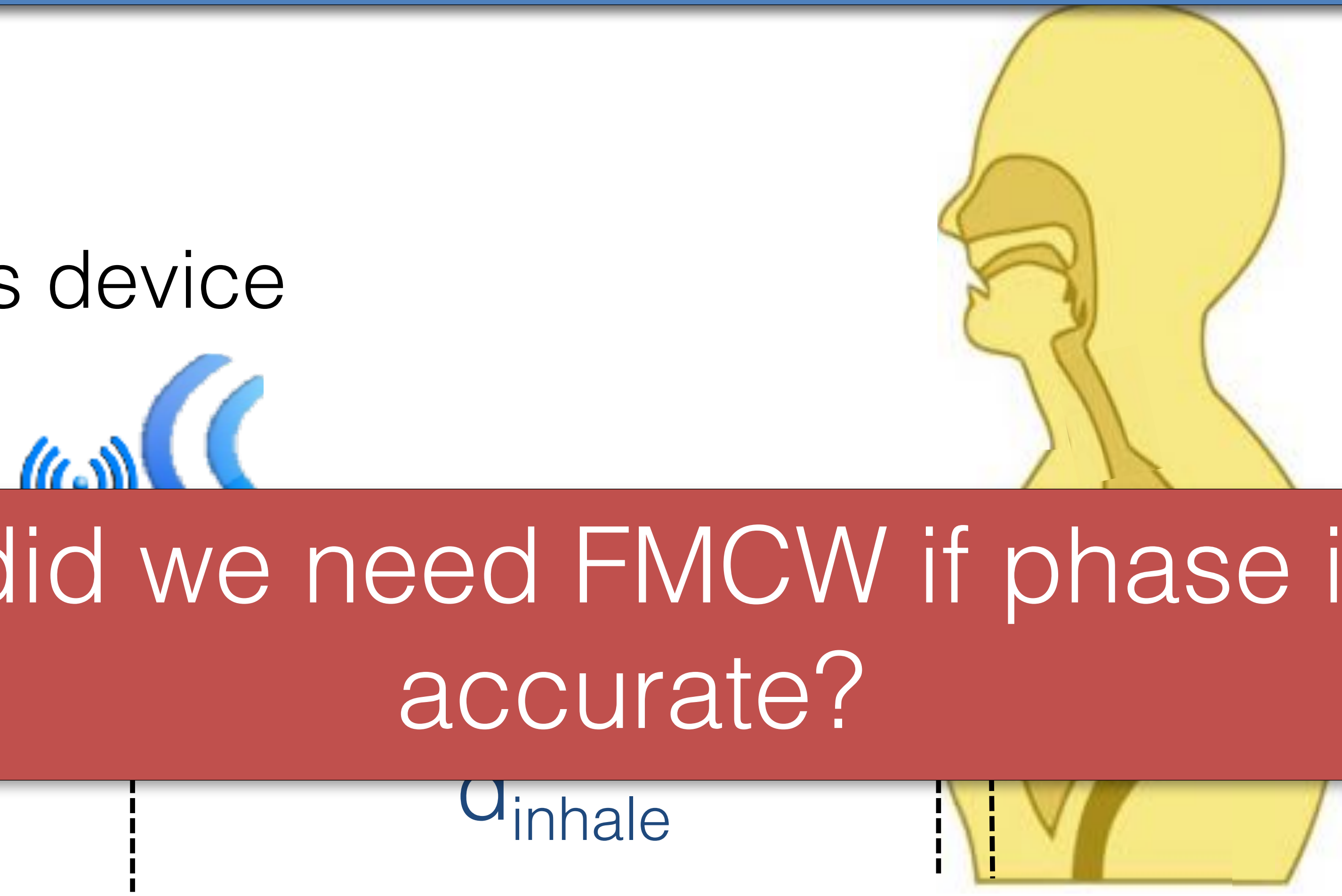
Why? How did we compute the resolution?

Solution: Use the phase of the wireless reflection



Why does phase allow us to get the distance at higher granularity?

Solution: Use the phase of the wireless reflection

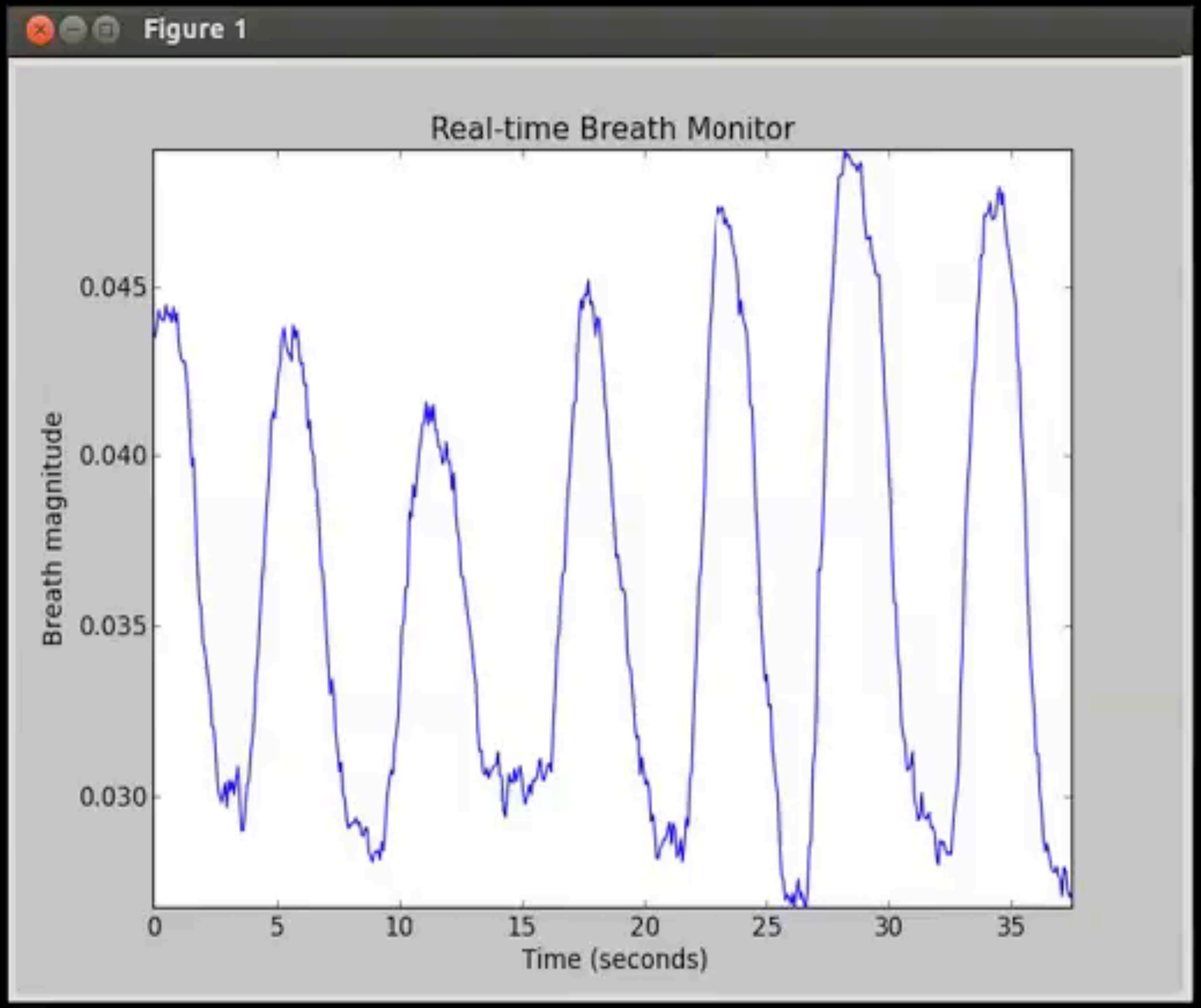


Why did we need FMCW if phase is so accurate?

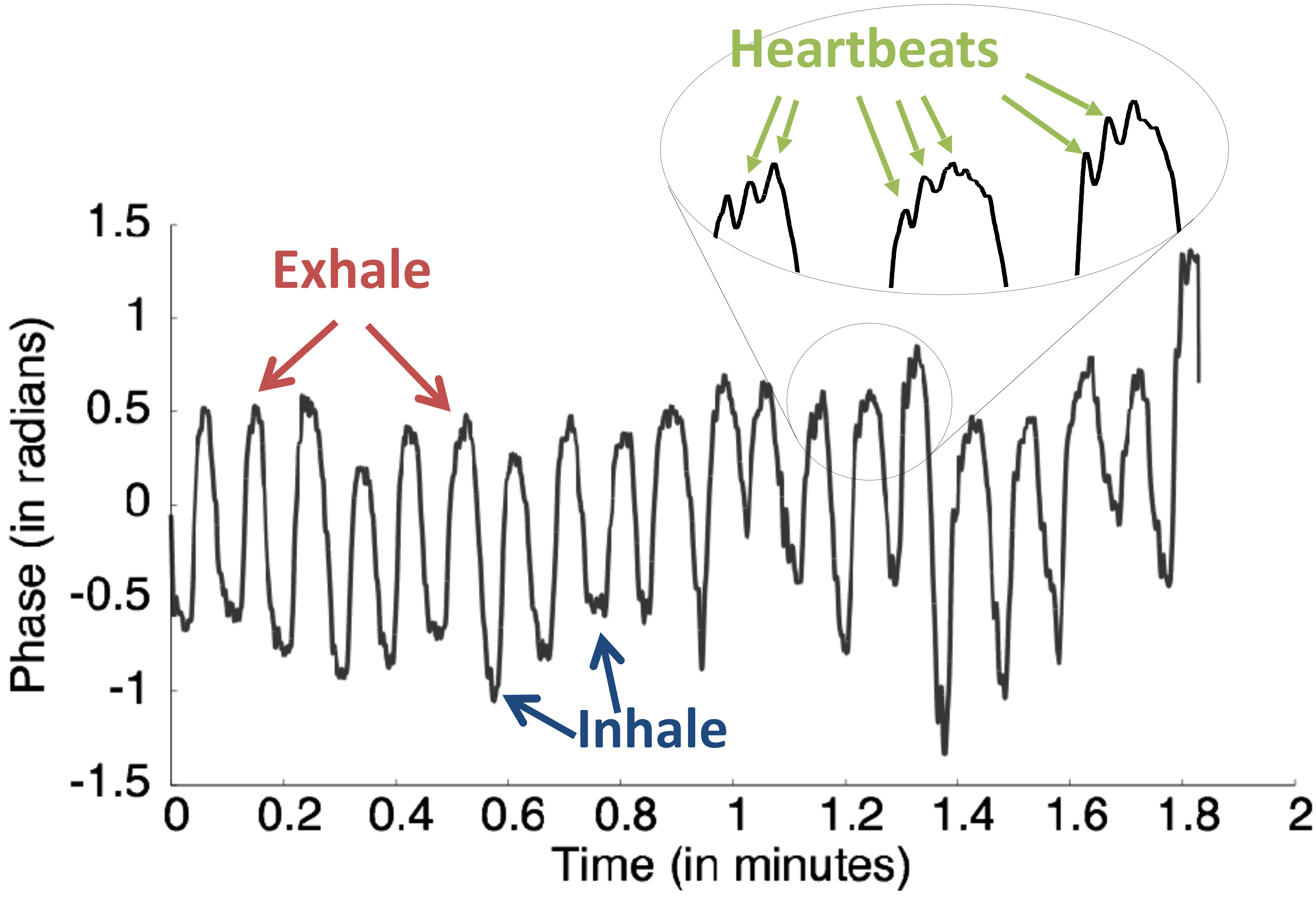
Wireless wave has a phase: $\boxed{\phi} = 2\pi \frac{\boxed{\text{distance}}}{\text{wavelength}}$

- Chest Motion changes distance
- Heartbeats also change distance

Breath Monitoring using Wireless (Vital-Radio, 2015)



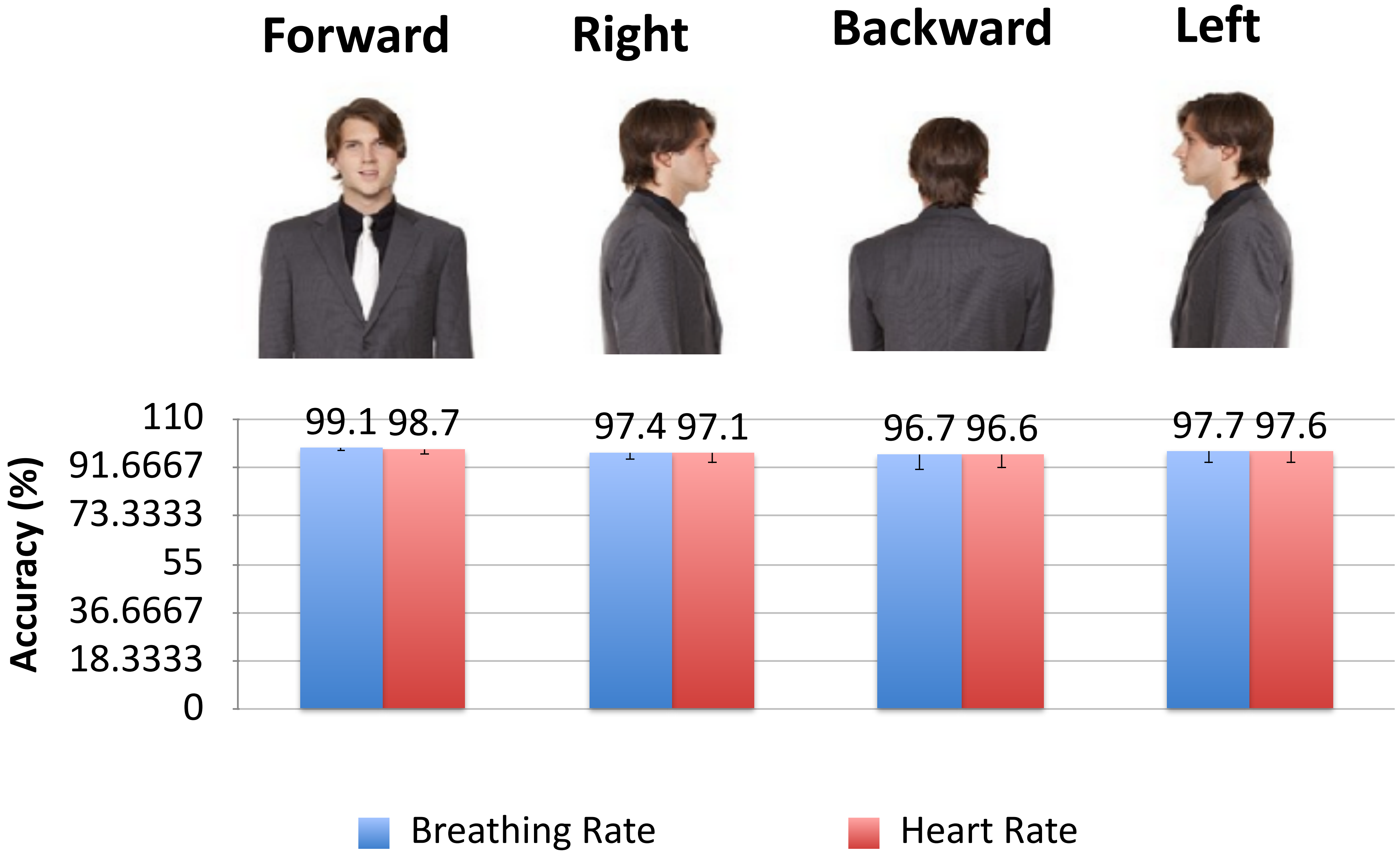
Let’s zoom in on these signals


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

Baby Monitoring

Accuracy vs. Orientation

User is 4m from device, with different orientations



Recent Advances

- Emotion Recognition
- Sleeping Monitoring
  - Positions, staging, timing
- Daily activities & action recognition
- Patient Movement Monitoring: Alzheimer’s, Parkinson’s, Multiple Sclerosis
- Cardiovascular Monitoring (Micro-cardiac events)

BroadbandCommunities

BUILDING A FIBER-CONNECTED WORLD MAGAZINE

Wi-Fi Becomes Sound Backbone for Motion Sensing and Smart-Home Monitoring

Share

November/December 2019 •

By Oleksiy Kravets | Cognitive Systems

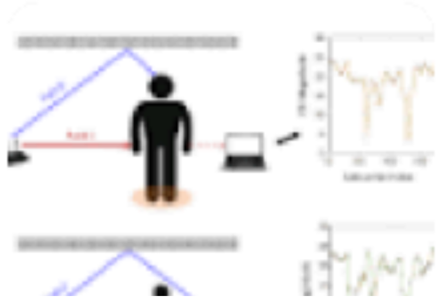
Service providers should look to thei
emerging motion-sensing and smart

Network World

Cisco moves WiFi roaming technology to wireless broadband consortium

Synced

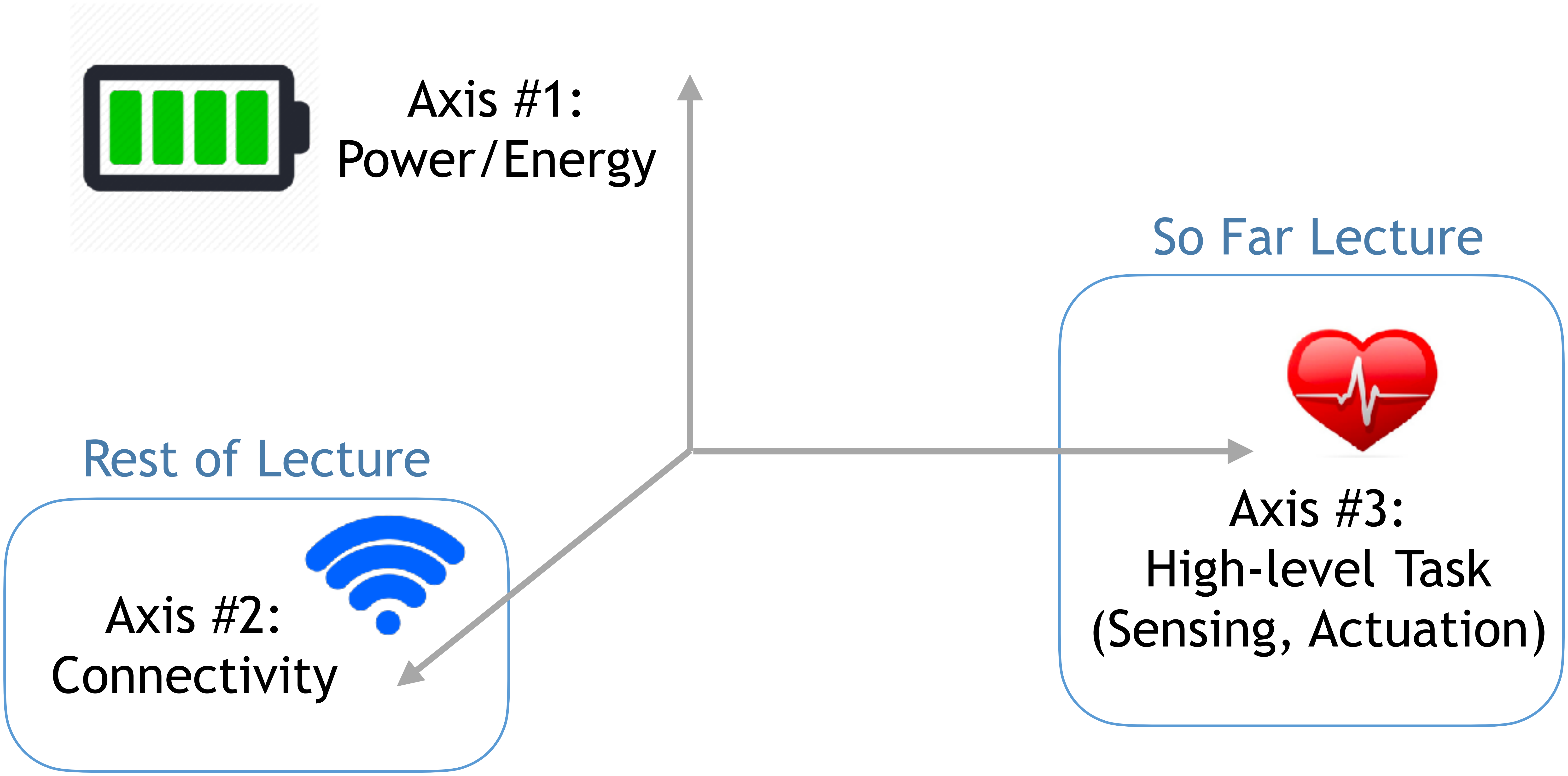
Samsung AI Uses WiFi Signals to Generate Consistent In-Home User Localization Data



Gizmodo

Motion Sensing Wifi Is a Limited But Fascinating Peek at the Future of the Smart Home

Main Components of IoT Systems



Underwater-to-Air Comm Applications

Submarine-Airplane Communication

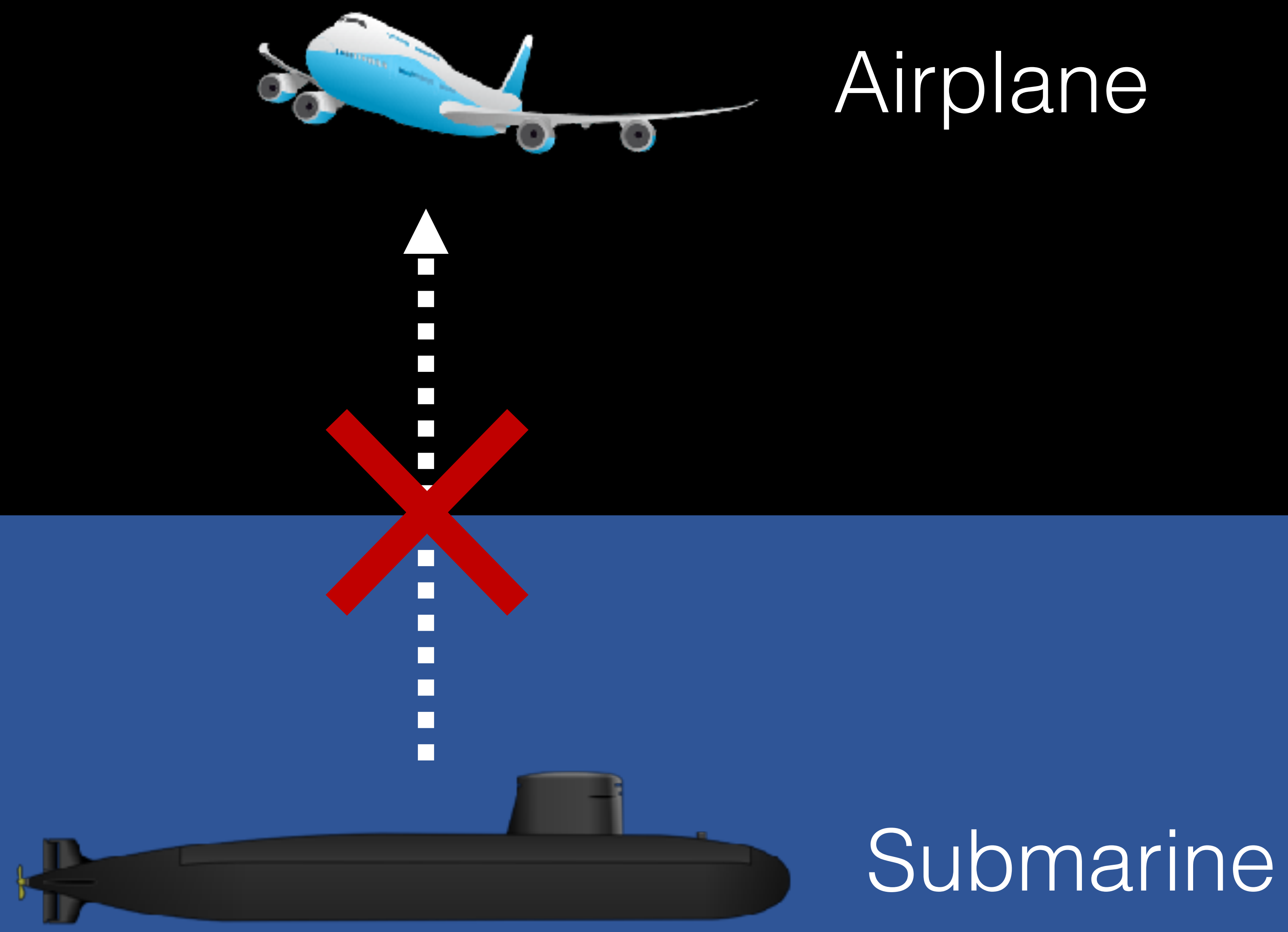
Finding Missing Airplanes

Ocean Scientific Exploration

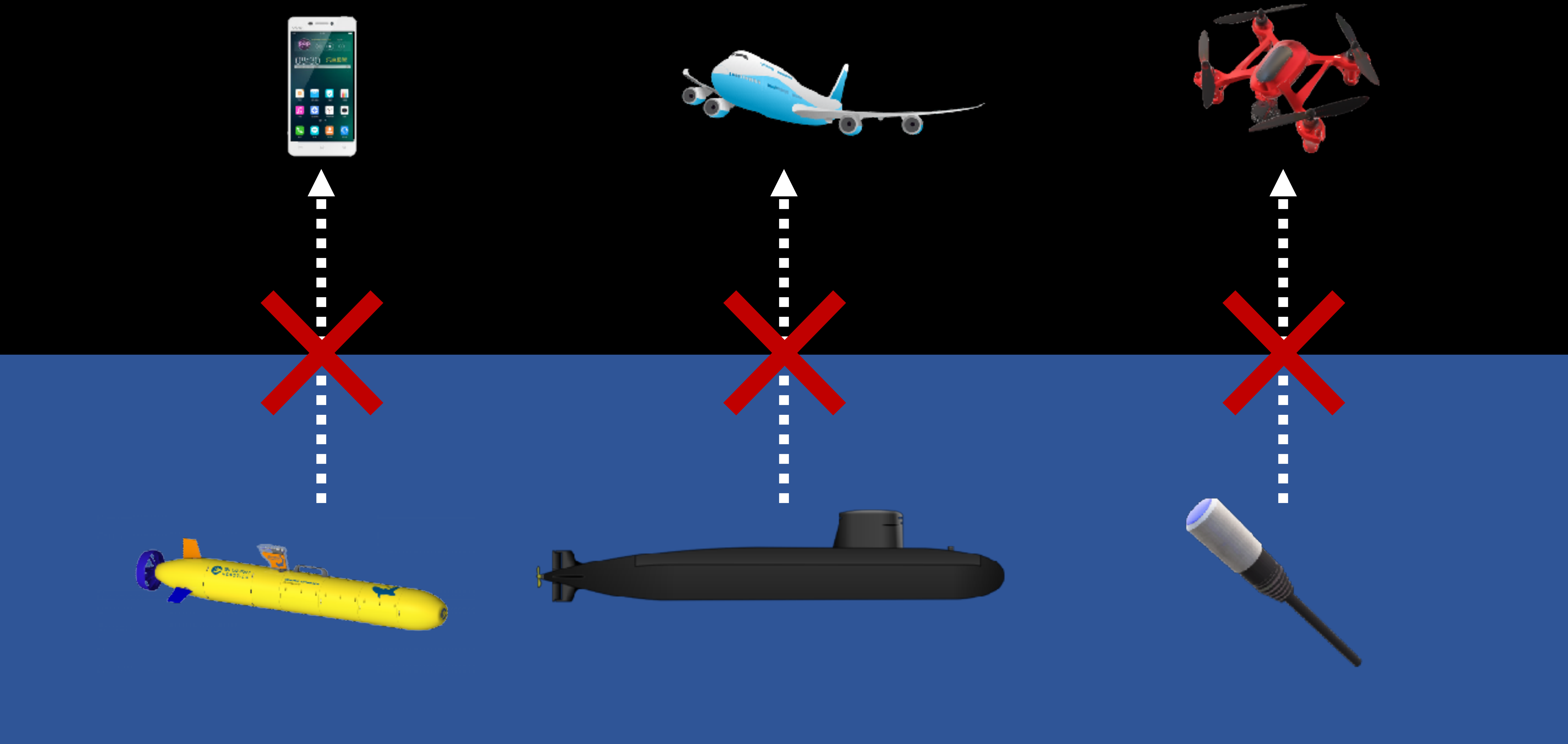
Underwater-to-Air Comm Applications

Why is it difficult?

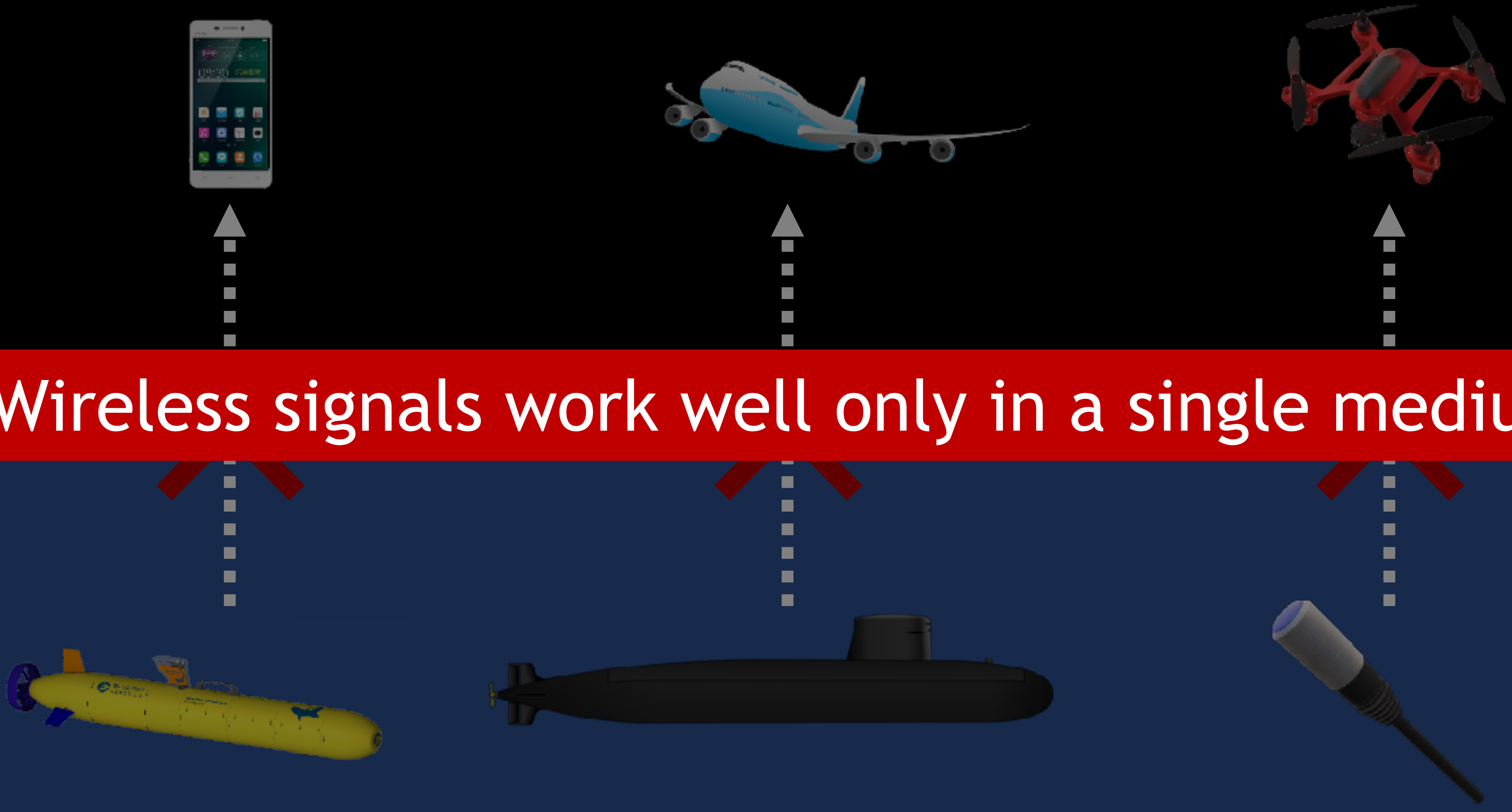
Submarines Cannot Communicate with Airplanes



Direct Underwater-Air Communication is Infeasible



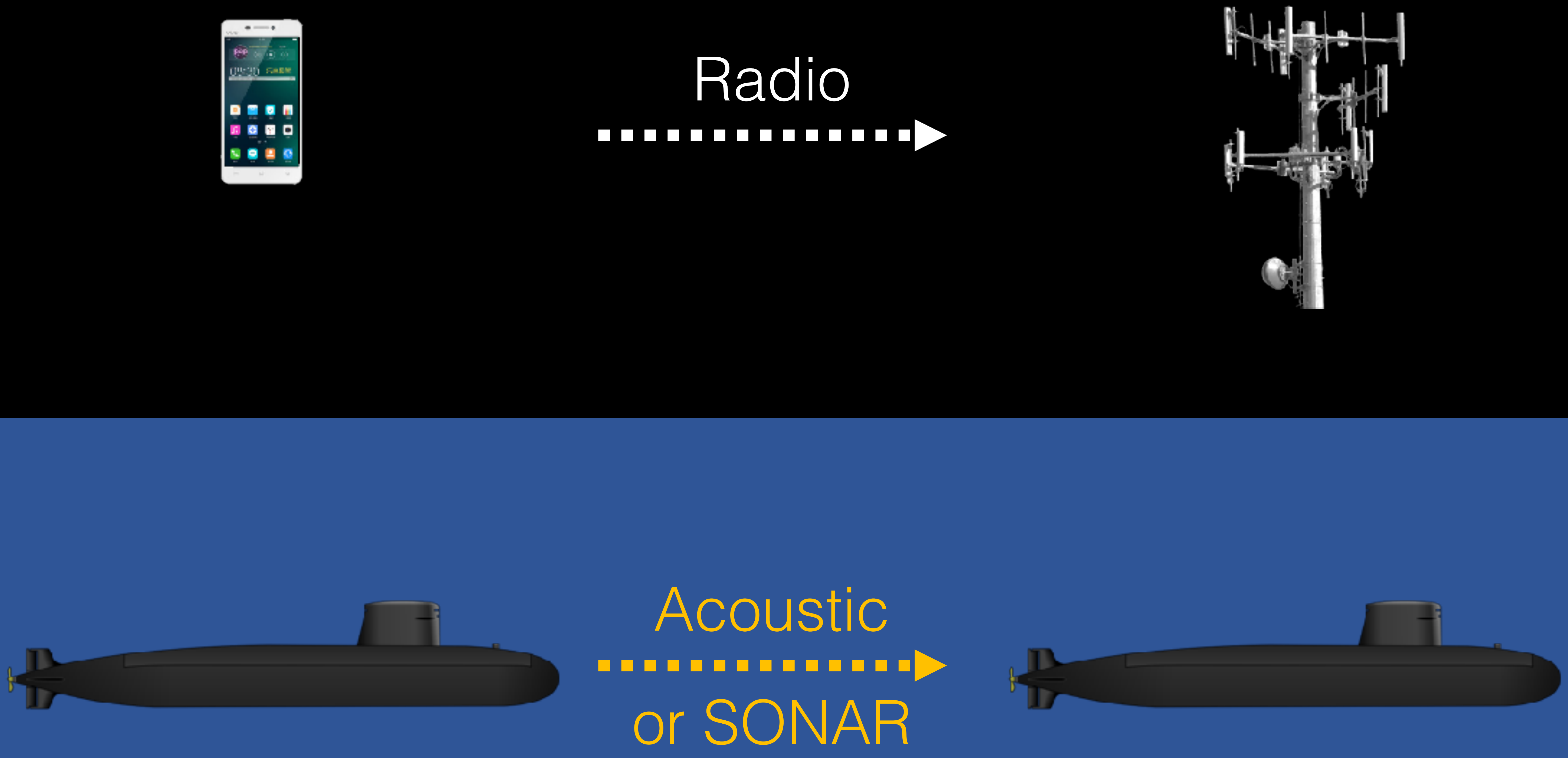
Direct Underwater-Air Communication is Infeasible



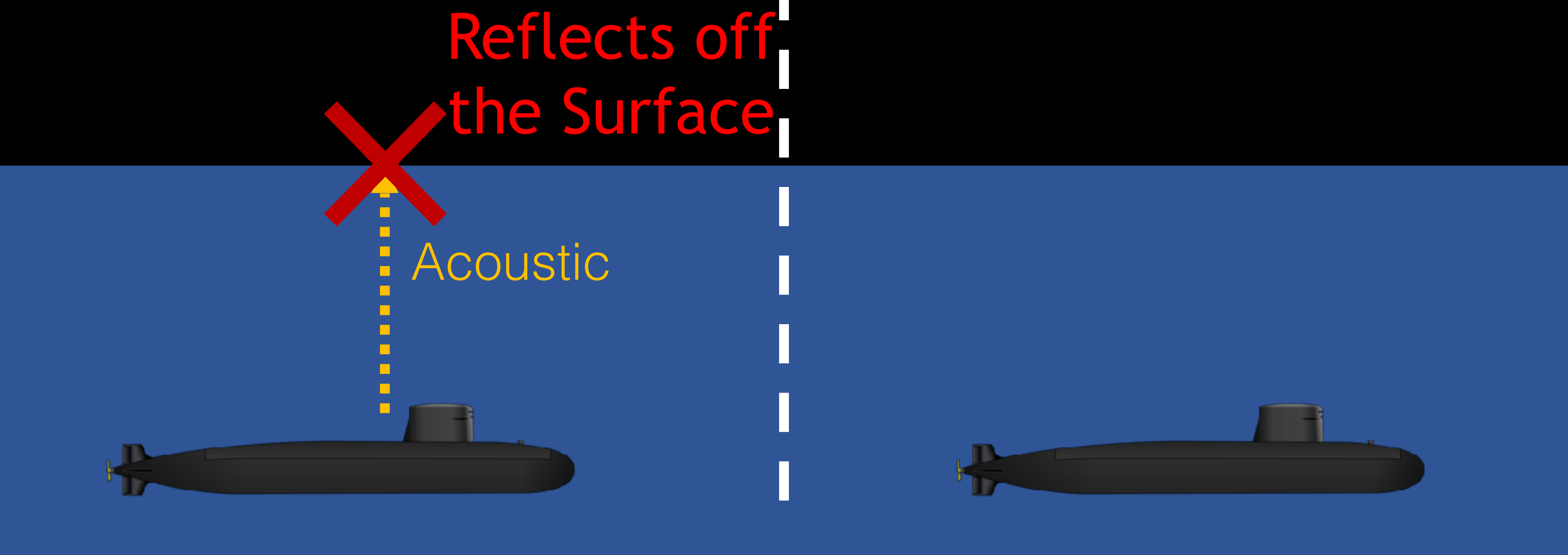
Wireless signals work well only in a single medium

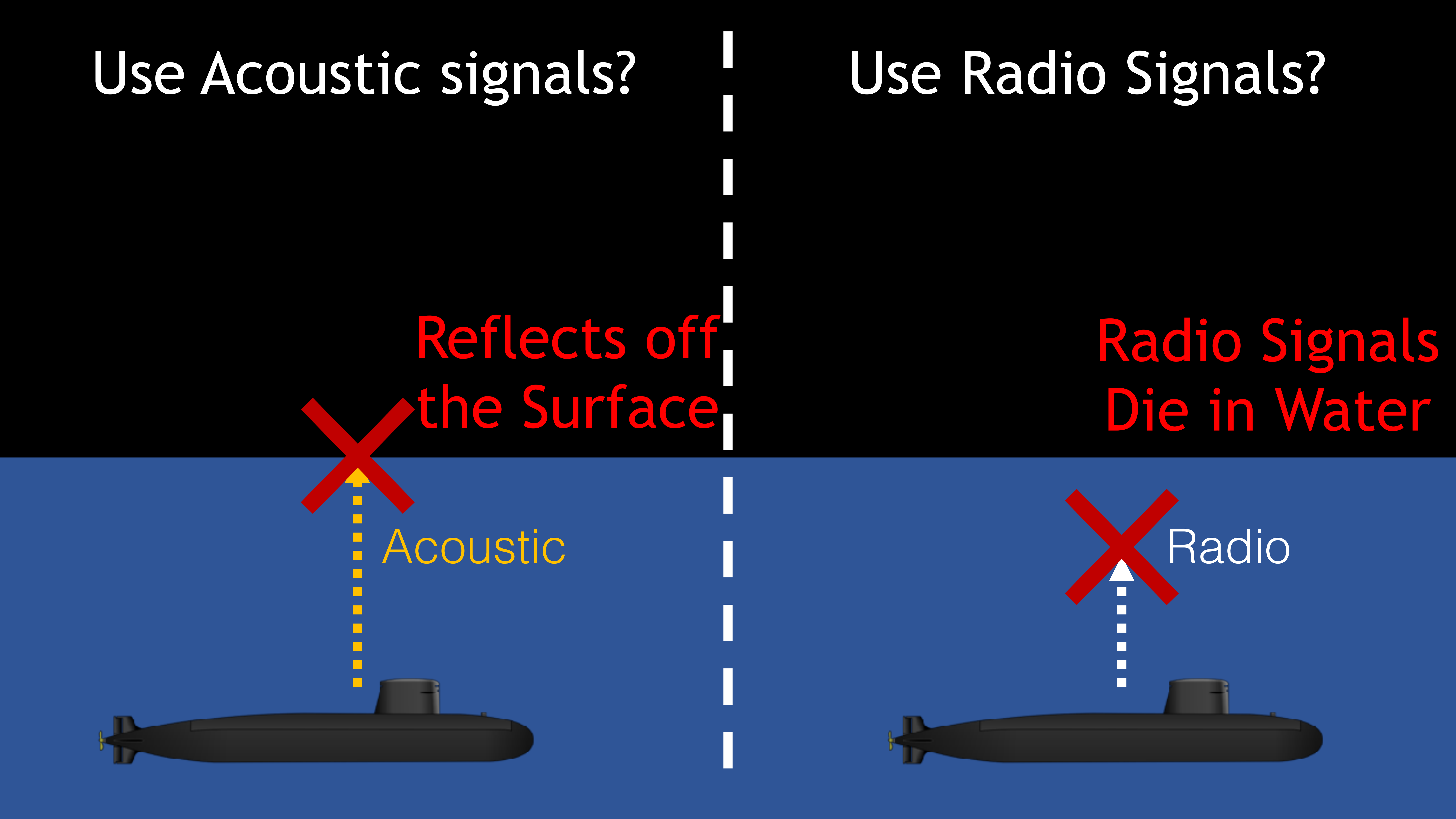
Wireless Signals Work Well Only in a Single Medium

Wireless Signals Work Well Only in a Single Medium



Use Acoustic signals?

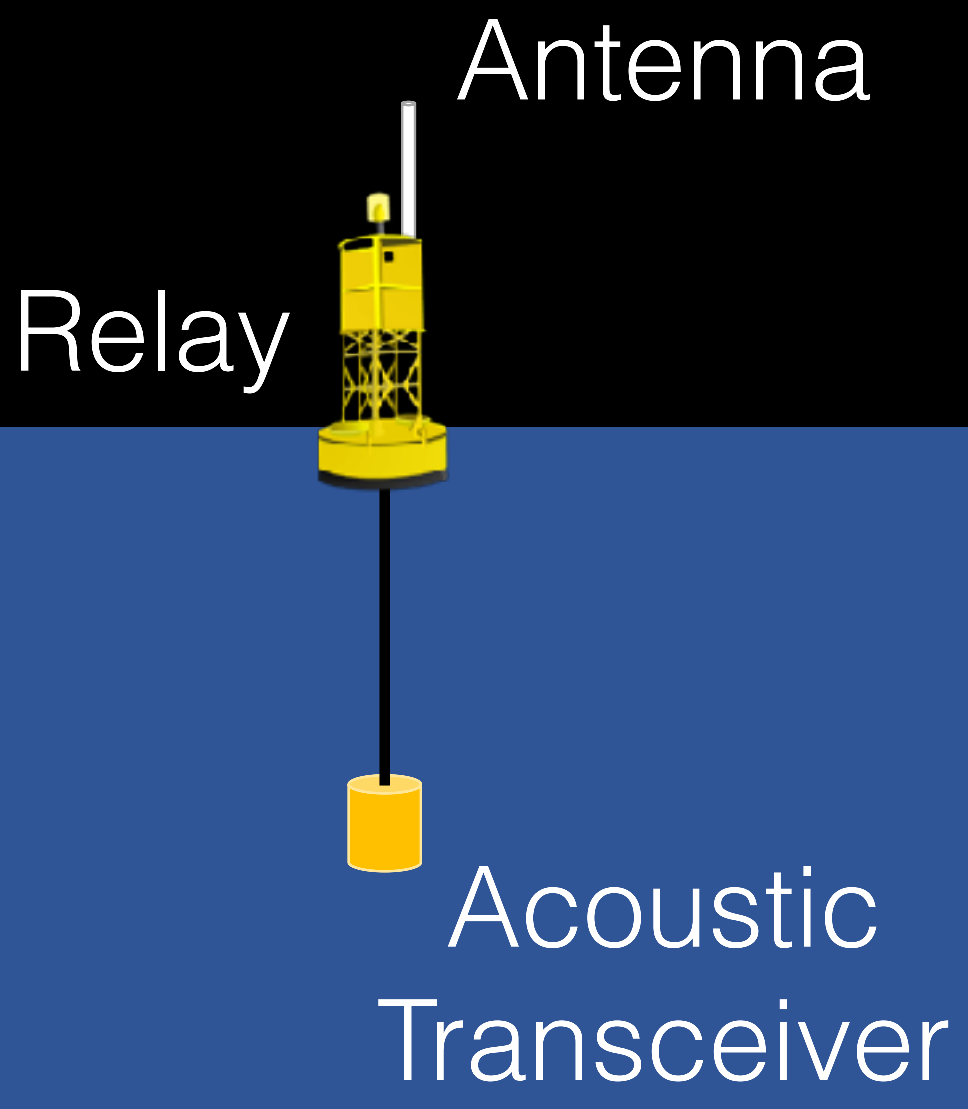



Use Acoustic signals?
Use Radio Signals?
Reflects off the Surface
Radio Signals Die in Water
Acoustic
Radio

What are today’s approaches for solving this problem?

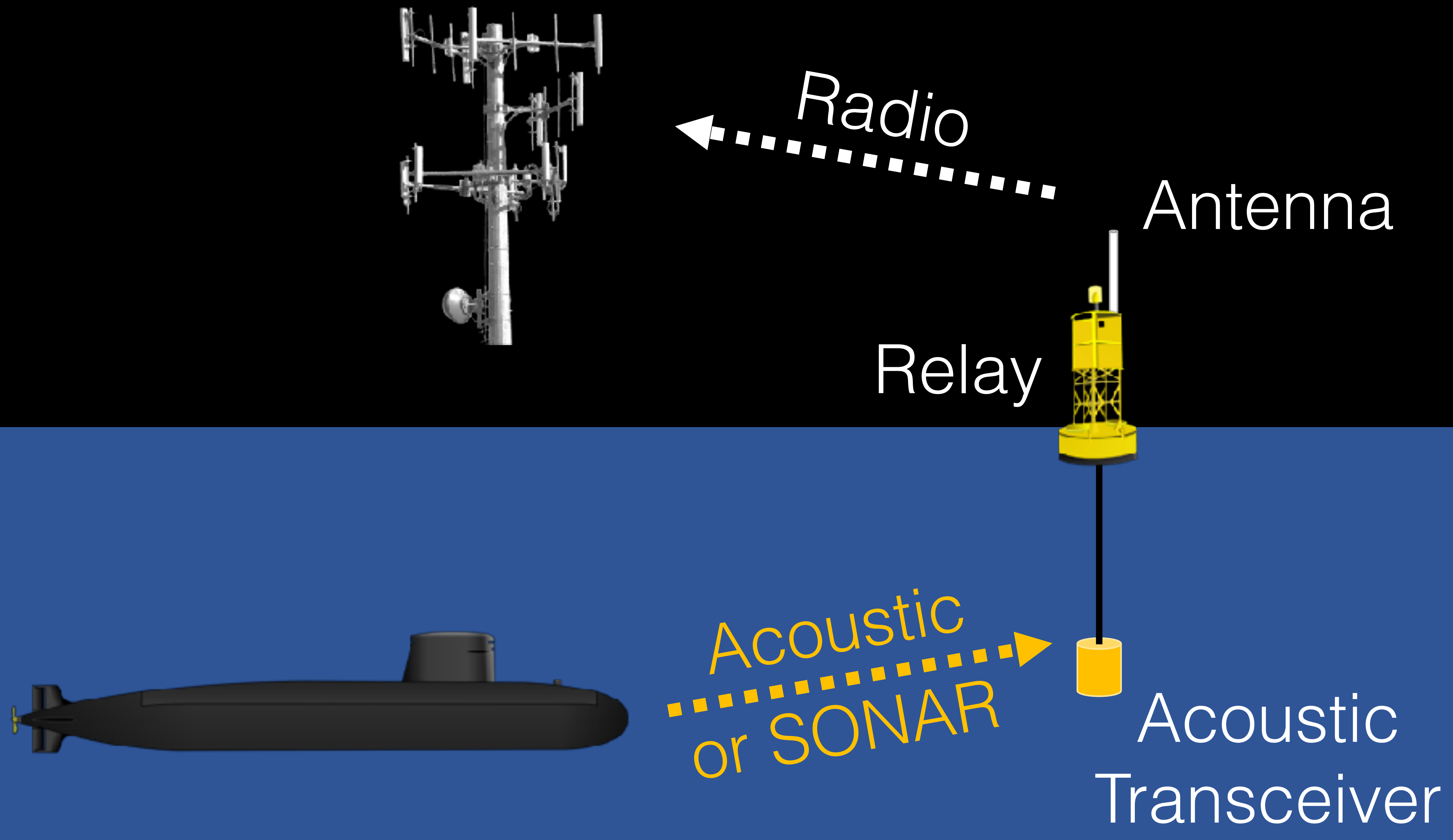
Approach #1: Relay Nodes

[OCEANS'07, ICC'11, ICC'14, Sensors'14]



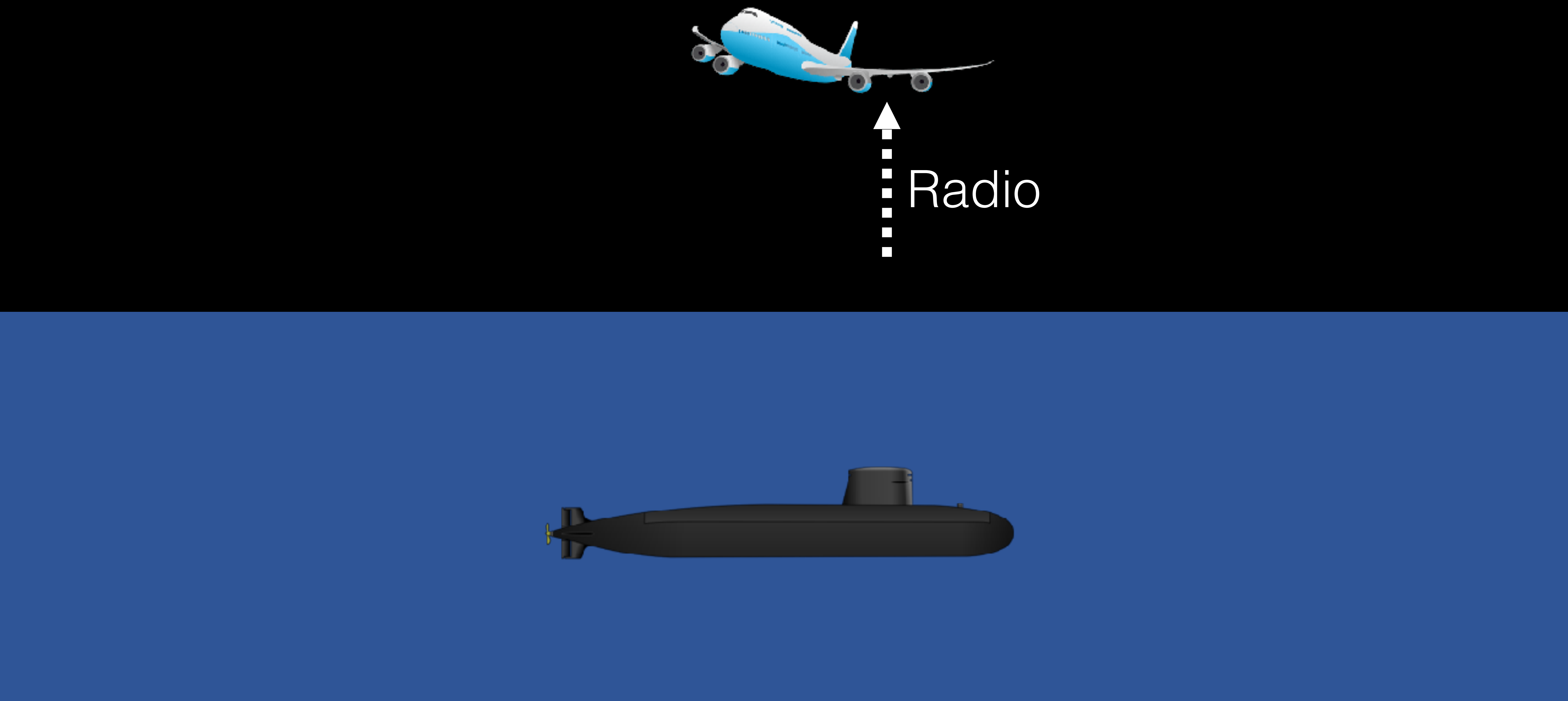
Approach #1: Relay Nodes

[OCEANS'07, ICC'11, ICC'14, Sensors'14]



Approach #2: Surfacing

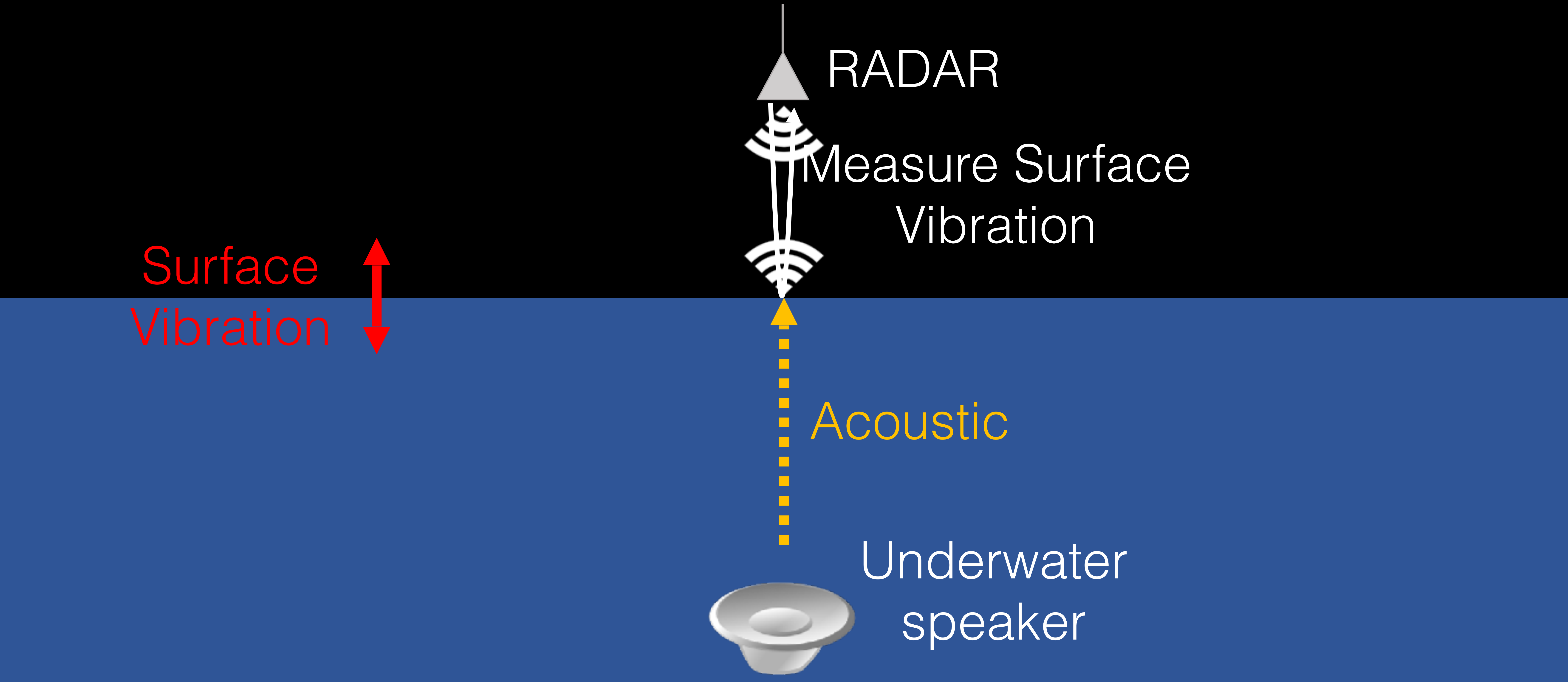
[ICRA'06, MOBICOM'07, OCEANS'10, ICRA'12]



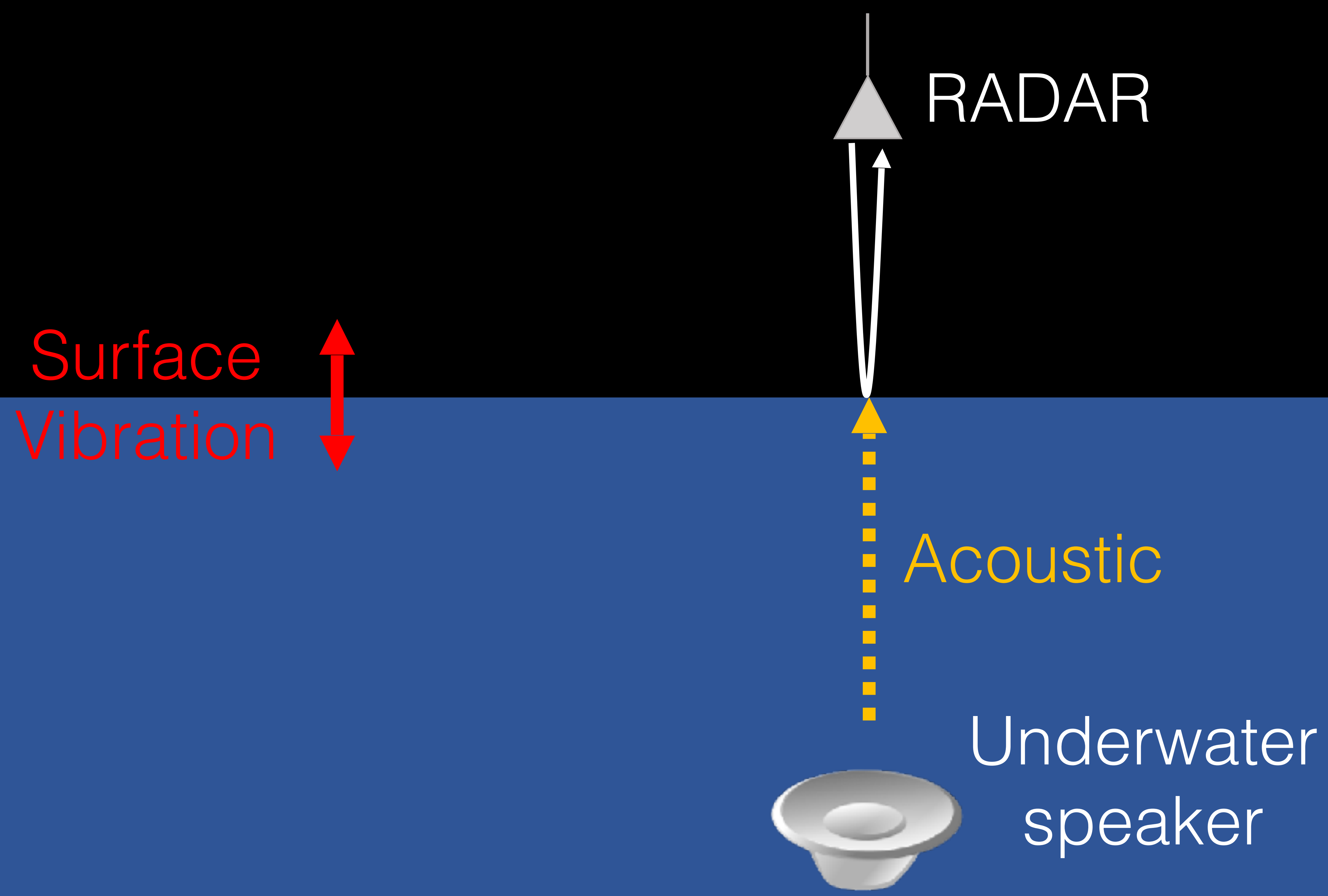
First Technology that Enables Wireless Communication Across the Water-Air Boundary

How does it work?

First Technology that Enables Wireless Communication Across the Water-Air Boundary



Translational Acoustic RF Communication (TARF)



Translational Acoustic RF Communication

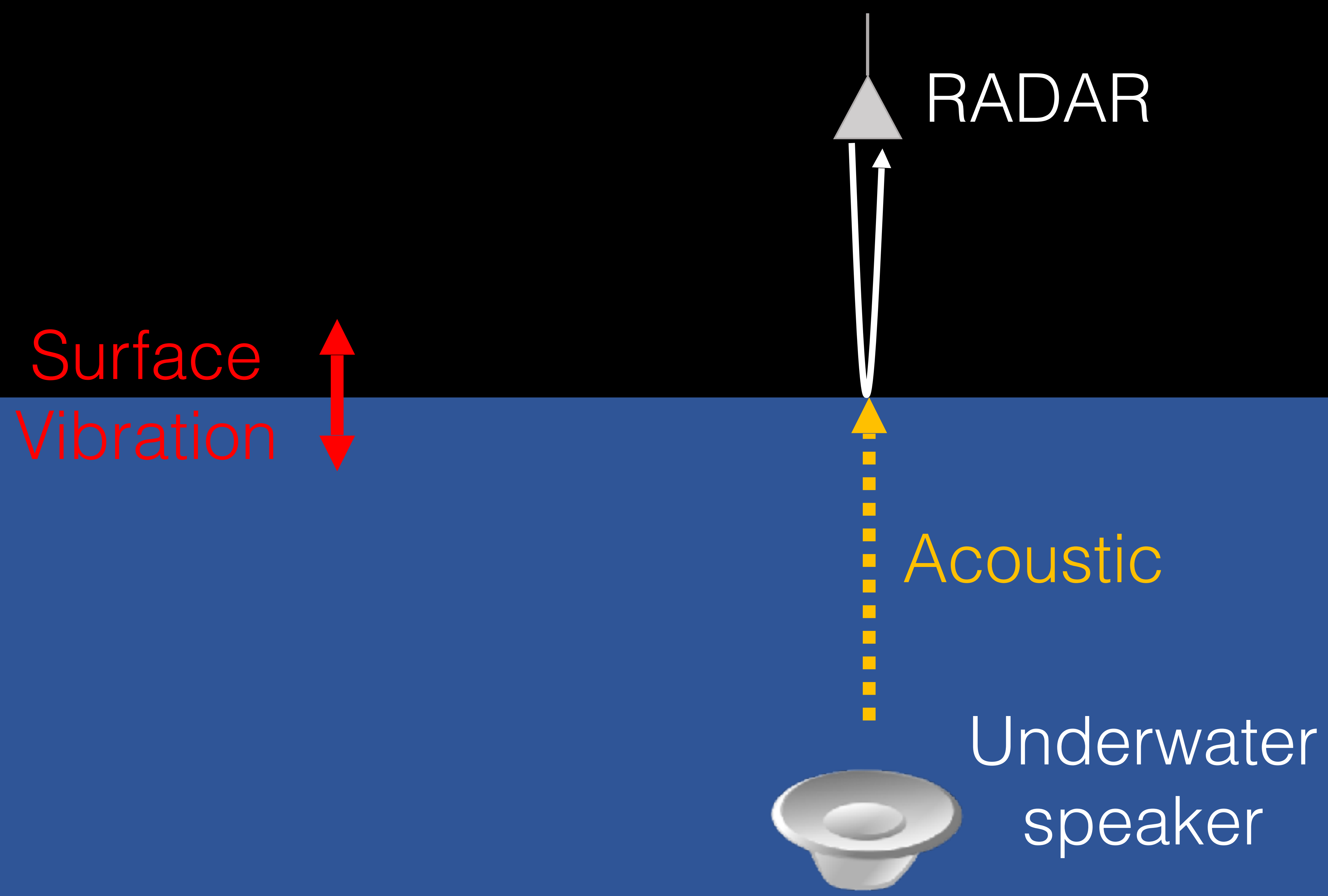
First technology that enables wireless communication across water-air interface

Theoretically achieves the best of both RF and acoustic signals in their respective media

Deals with practical challenges of communicating across water-air interface including natural surface waves

Implemented and tested in practical environments

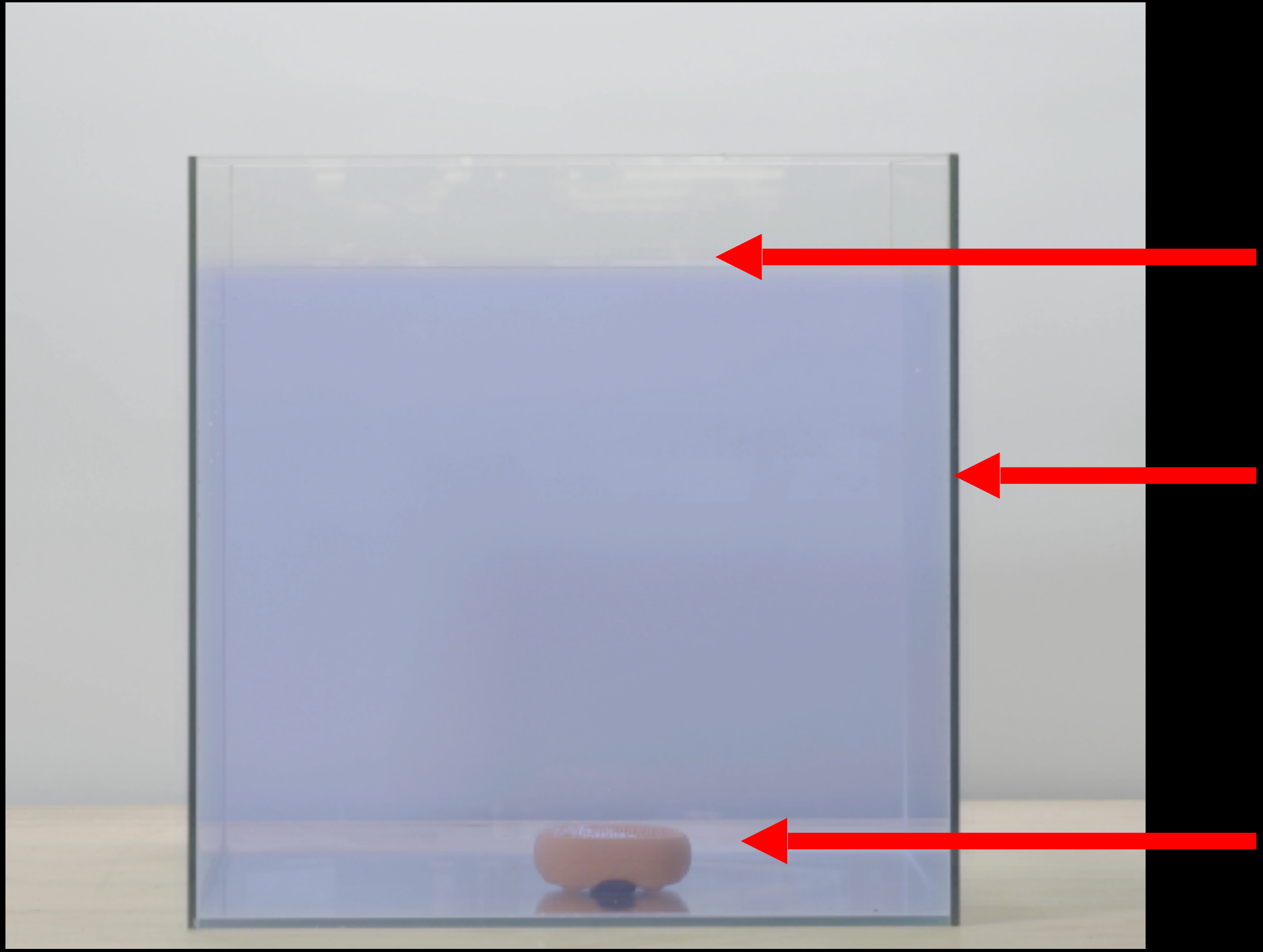
Key Idea



Can We Sense the Surface Vibration Caused by the Transmitted Underwater Acoustic Signal?

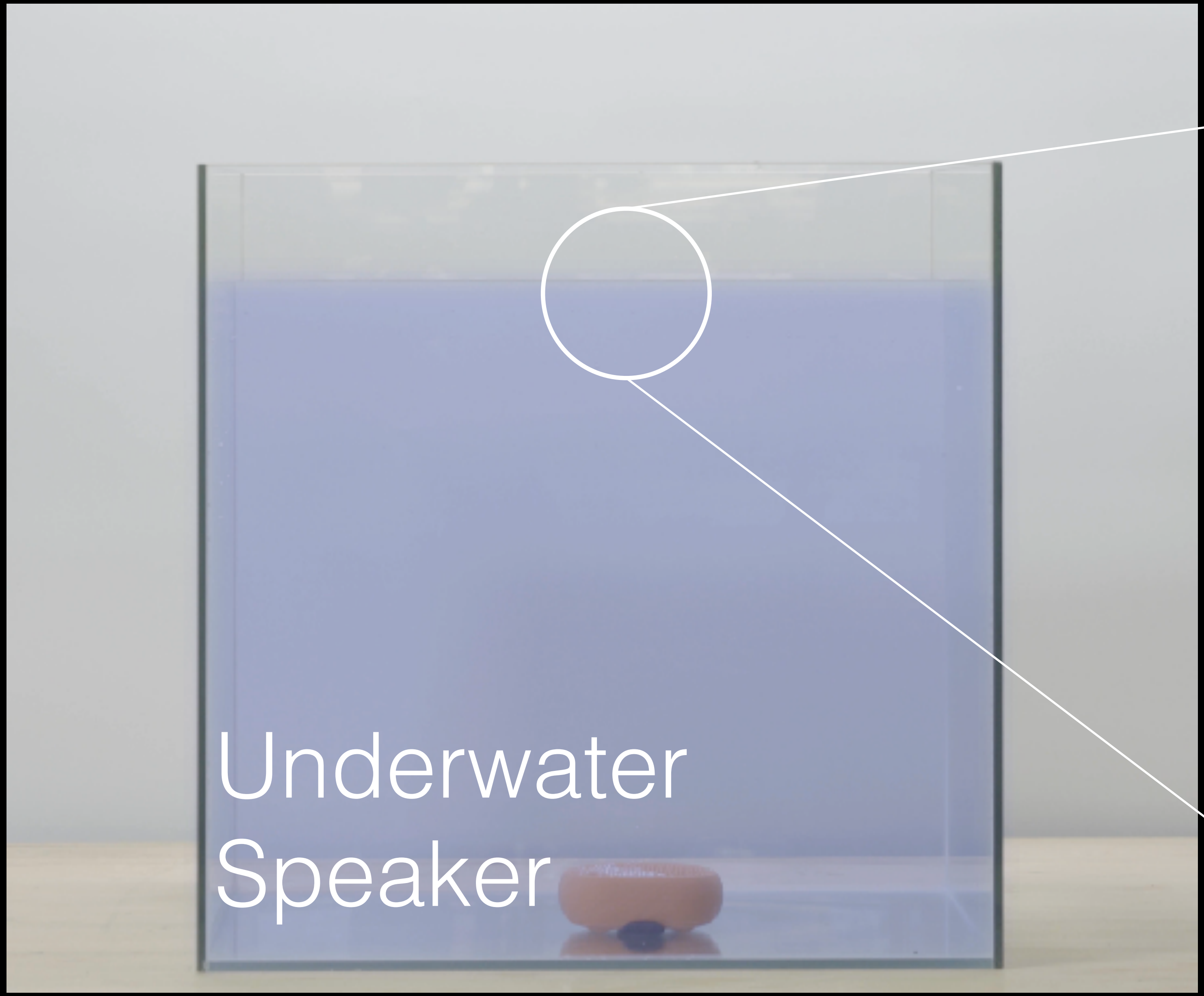
Recording the Surface Vibration

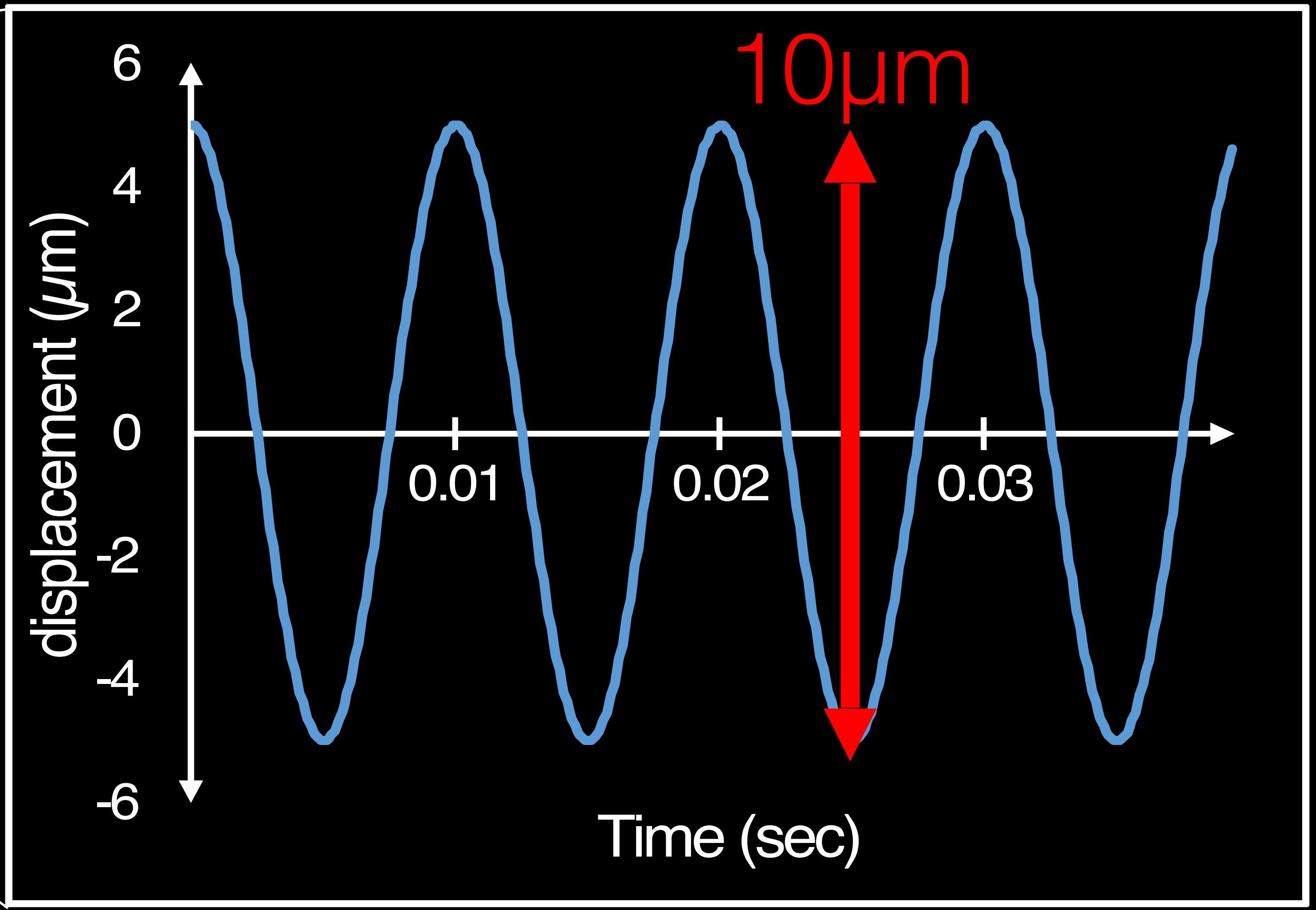
<u>Experiment:</u> Transmit Acoustic Signals at 100Hz



Recording the Surface Vibration

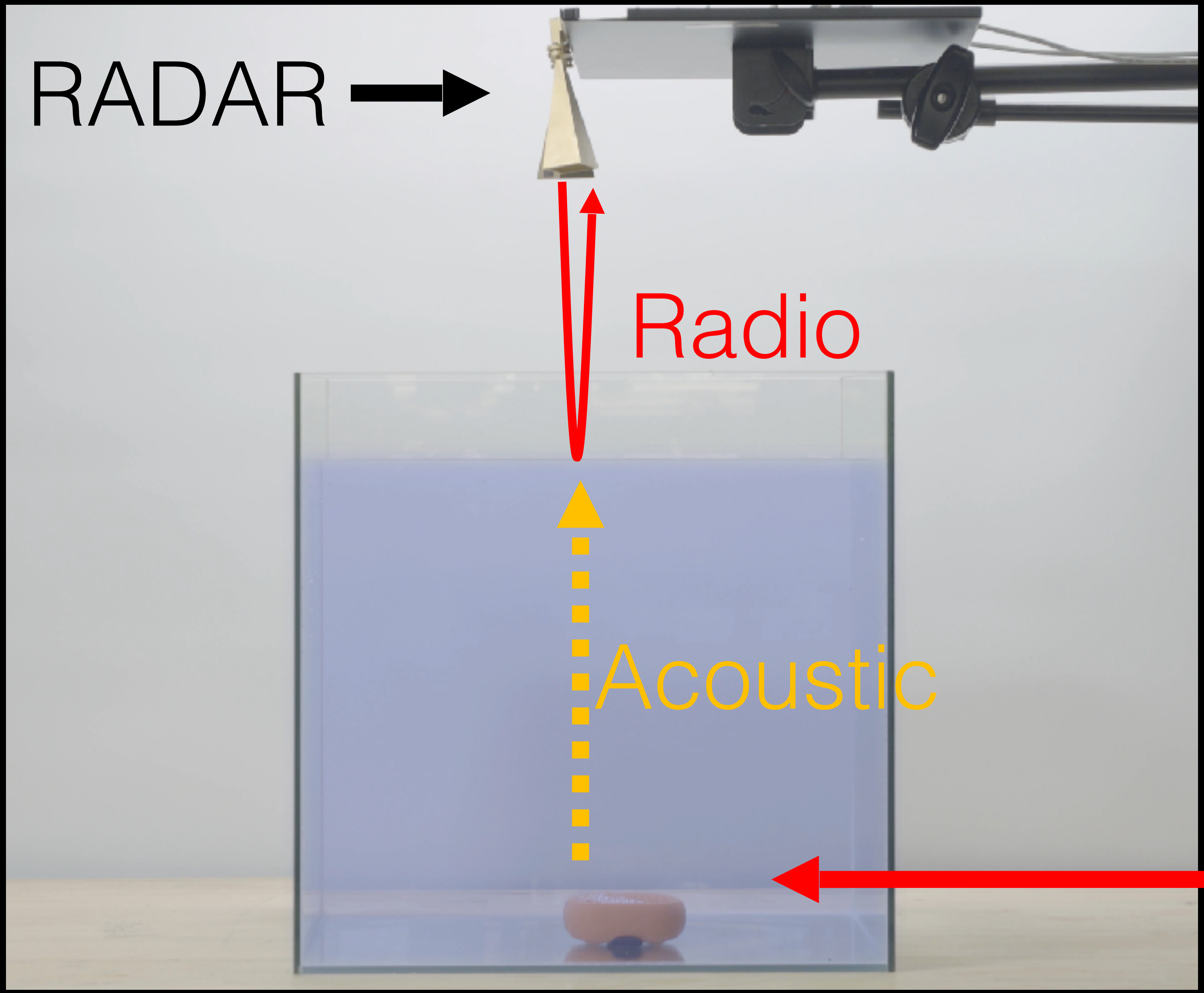
Experiment: Transmit Acoustic Signals at 100Hz





How Can We Sense Microscale Vibration?

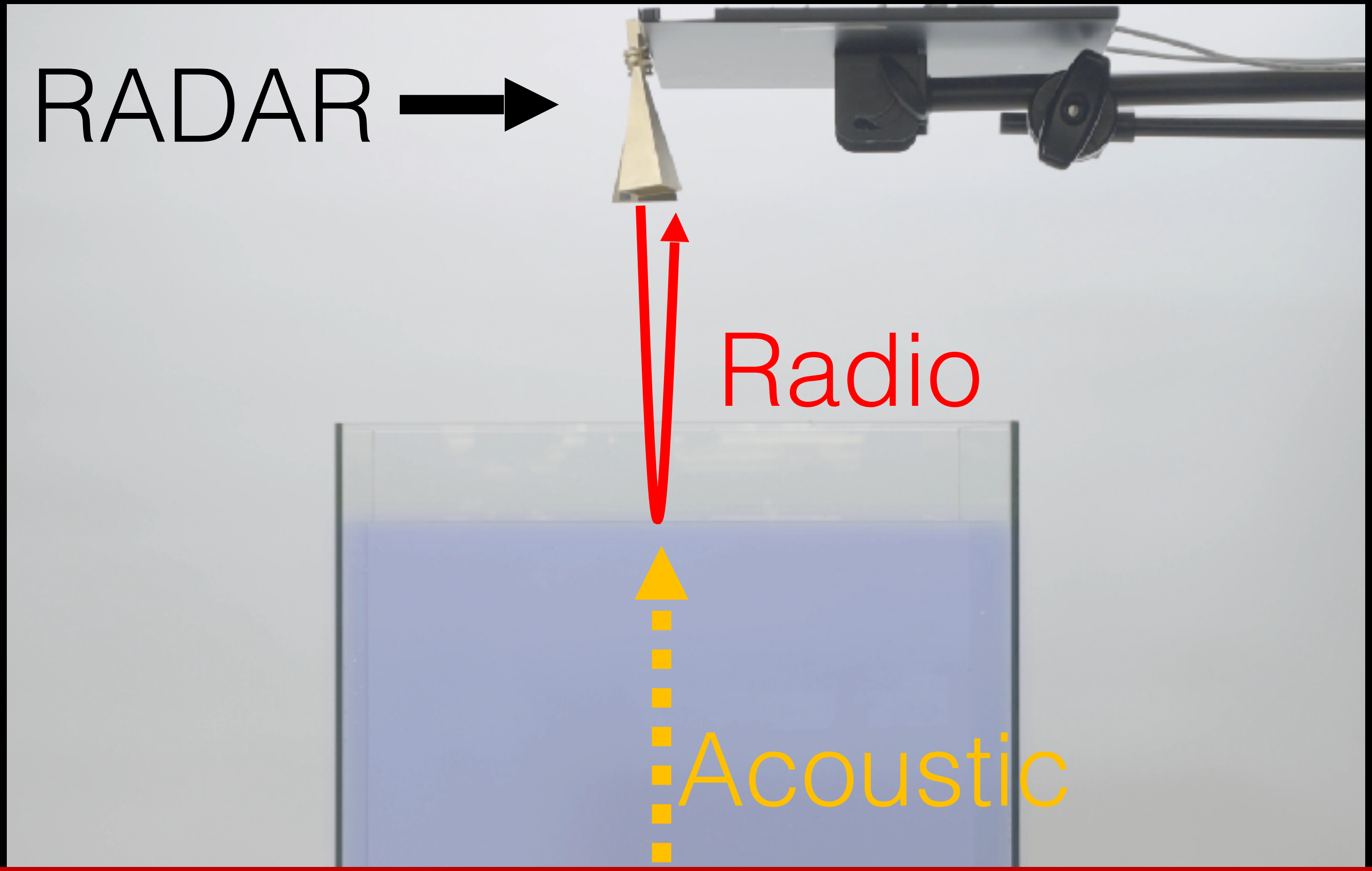
Idea: Use RADAR to measure the surface vibration



Underwater
Speaker

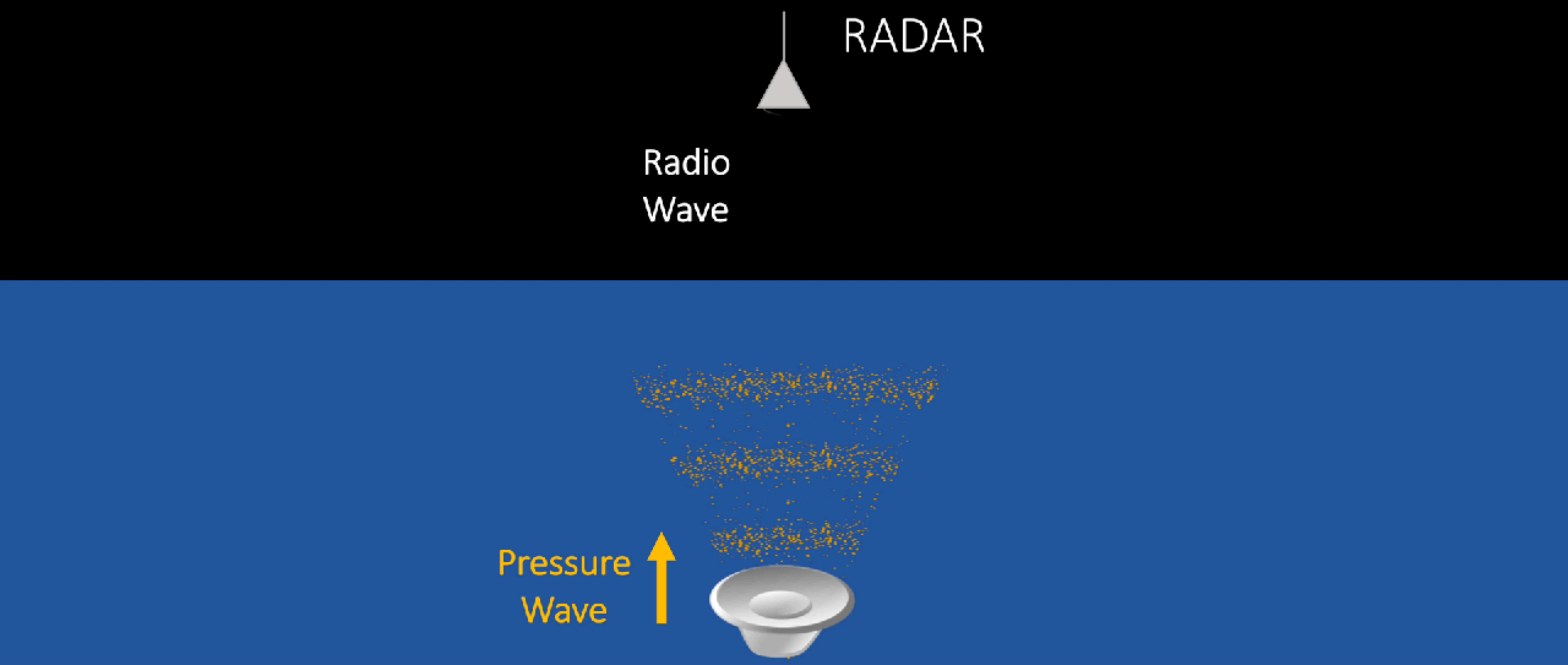
How Can We Sense Microscale Vibration?

Idea: Use RADAR to measure the surface vibration



<u>Problem:</u> Measuring micrometer vibrations requires 100s of THz of bandwidth → Impractical & Costly

Solution: Measure Changes in Displacement Using the Phase of Millimeter-Wave RADAR



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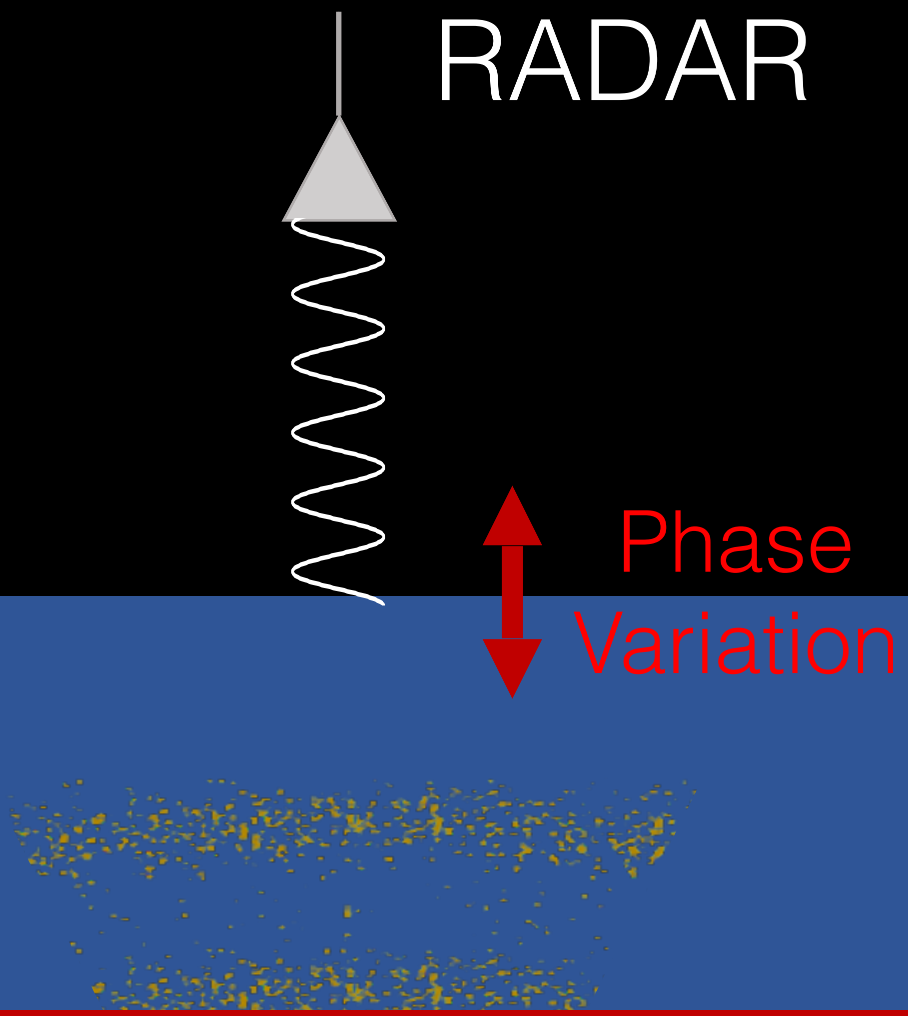


10μm

$$Phase = 360 \times \frac{displacement}{wavelength}$$

5mm

Phase Variation = 0.72degrees

The phase of the milimeter-wave RADAR encodes transmitted information from underwater

Natural Surface Waves Mask the Signal

On Calm Days, Ocean Surface Ripples (Capillary Waves)
Have 2cm Peak-to-Peak Amplitude

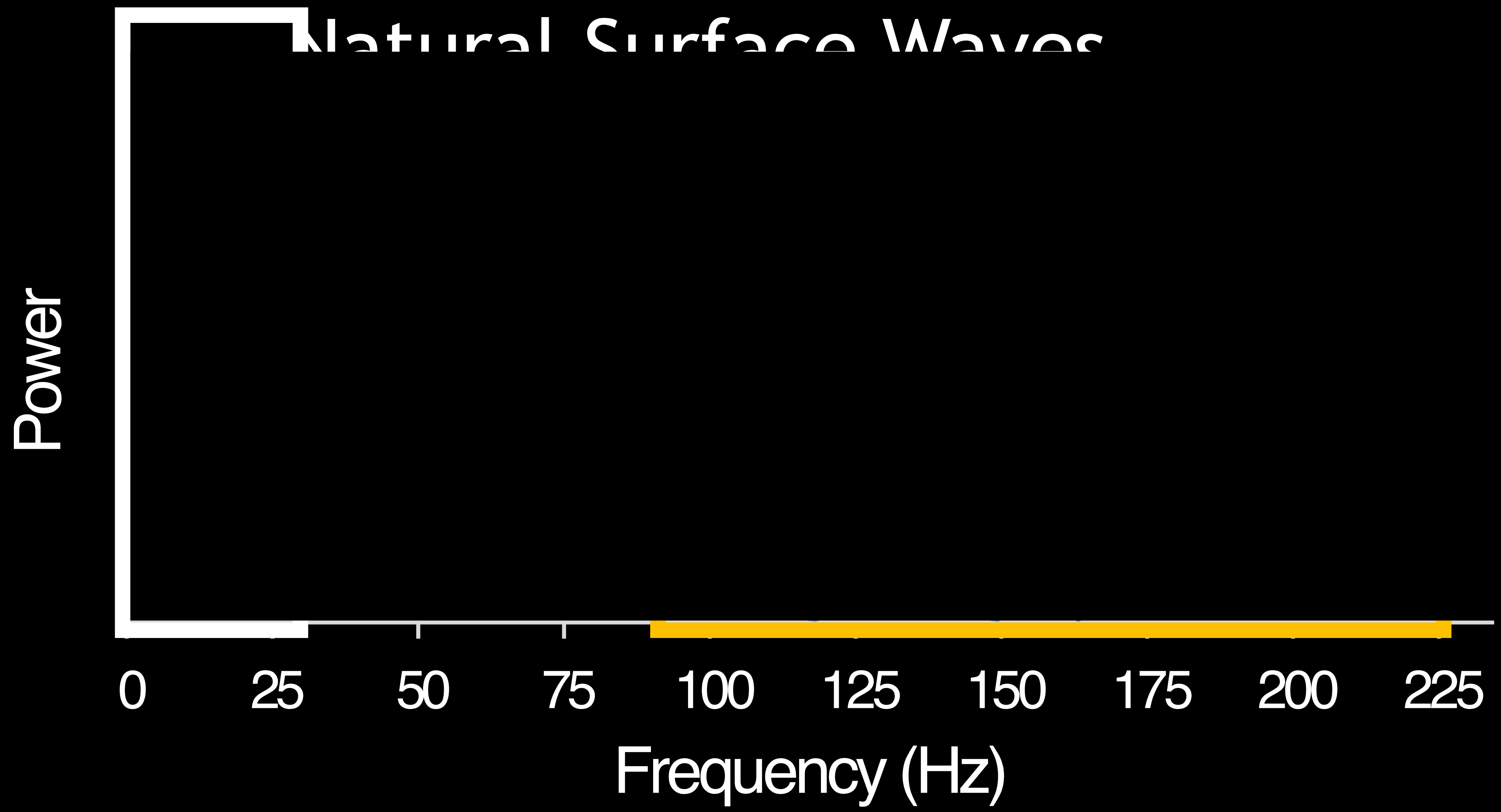
↓

1,000 Times Larger than Surface Vibration
Caused by the Acoustic Signal

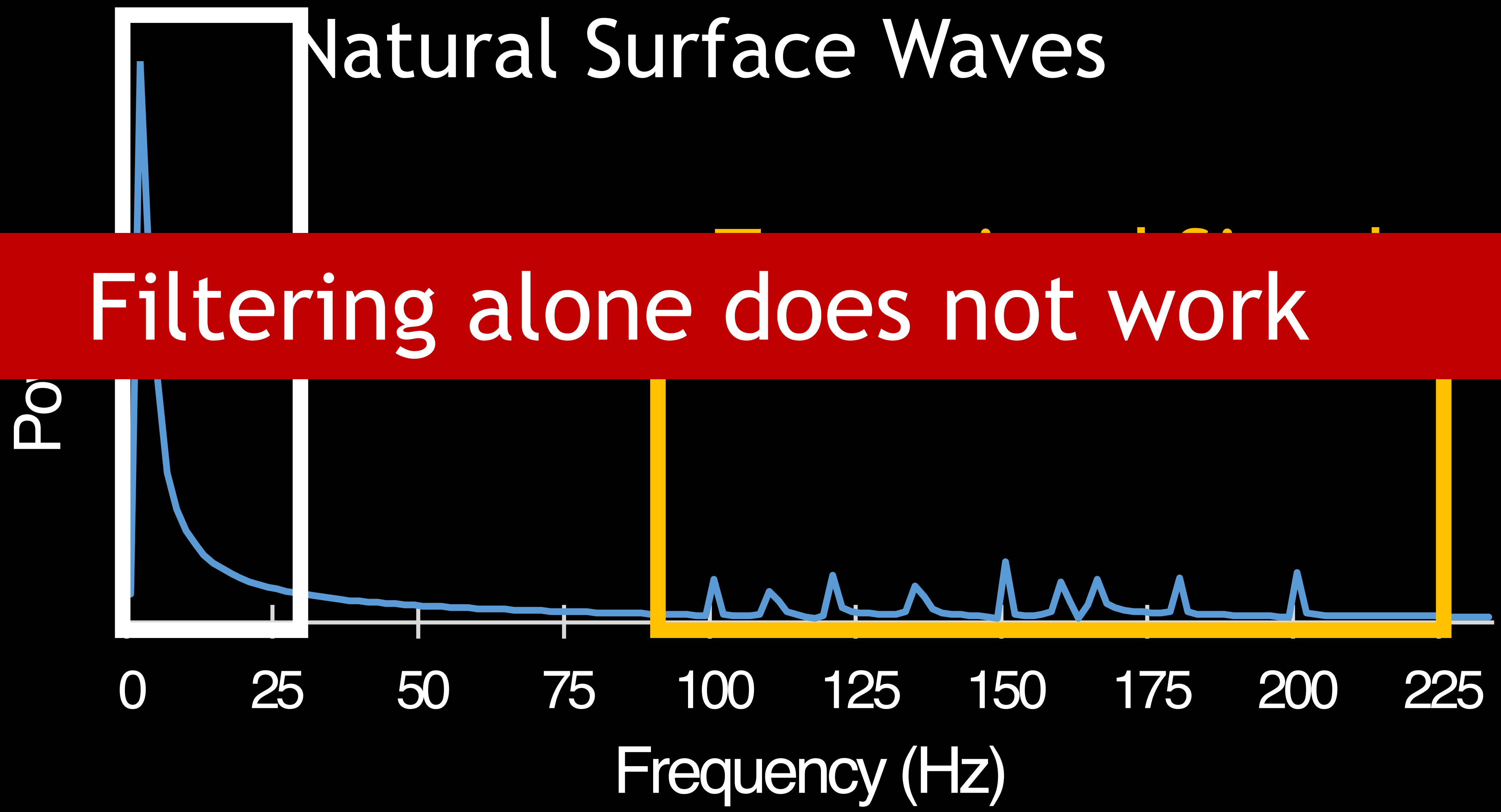
Natural Surface Waves Can Be Treated as Structured Interference and Filtered Out

	Frequency
Naturally occurring waves (e.g., ocean waves) are relatively slow	→ 1 – 2Hz
Acoustic signals are transmitted at higher frequencies	→ 100 – 200Hz

Natural Surface Waves Can Be Treated as Structured Interference and Filtered Out



Natural Surface Waves Can Be Treated as Structured Interference and Filtered Out



Filtering alone does not work

Dealing with Waves

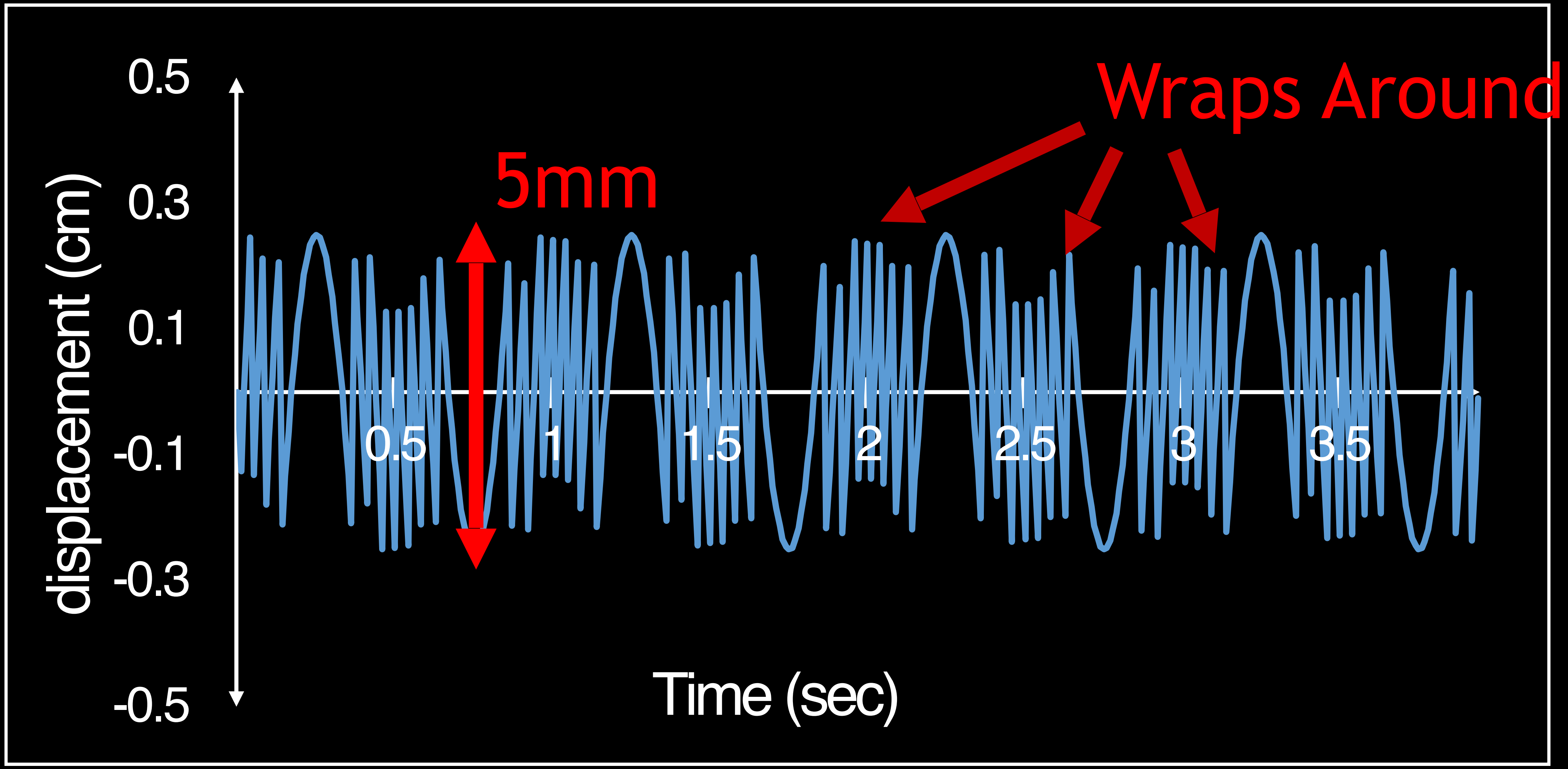
$$Angle = 360 \times \frac{displacement}{wavelength}$$

Dealing with Waves

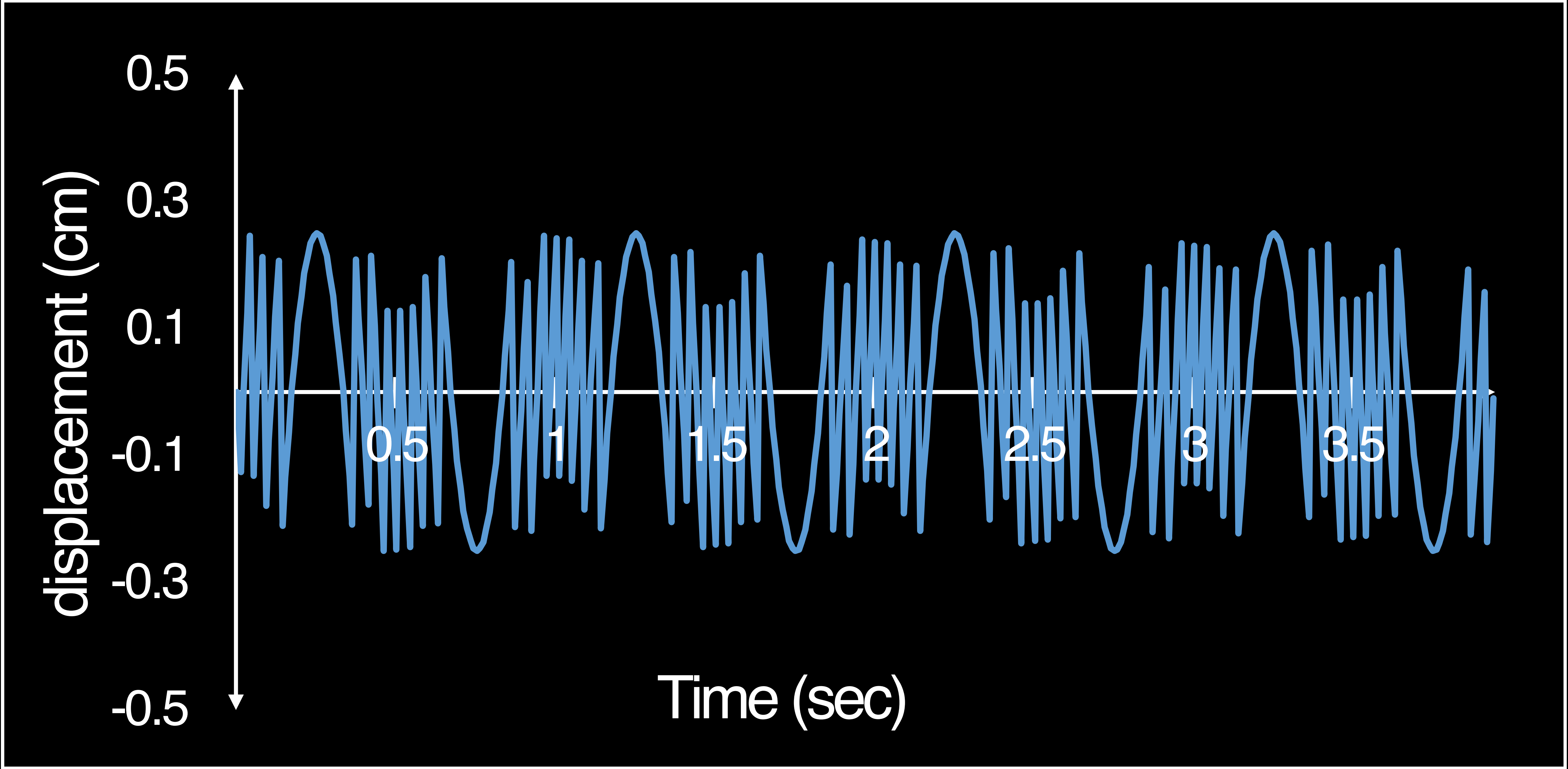
$$Angle = 360 \times \frac{displacement}{wavelength} \; mod \; 360$$

Dealing with Waves

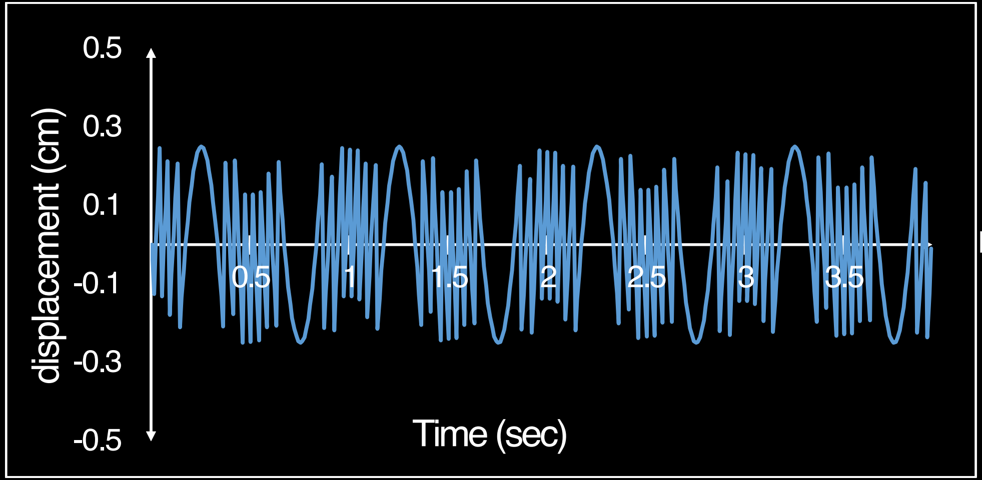
$$Angle = 360 \times \frac{displacement}{wavelength} \quad mod\ 360$$



Dealing with Waves

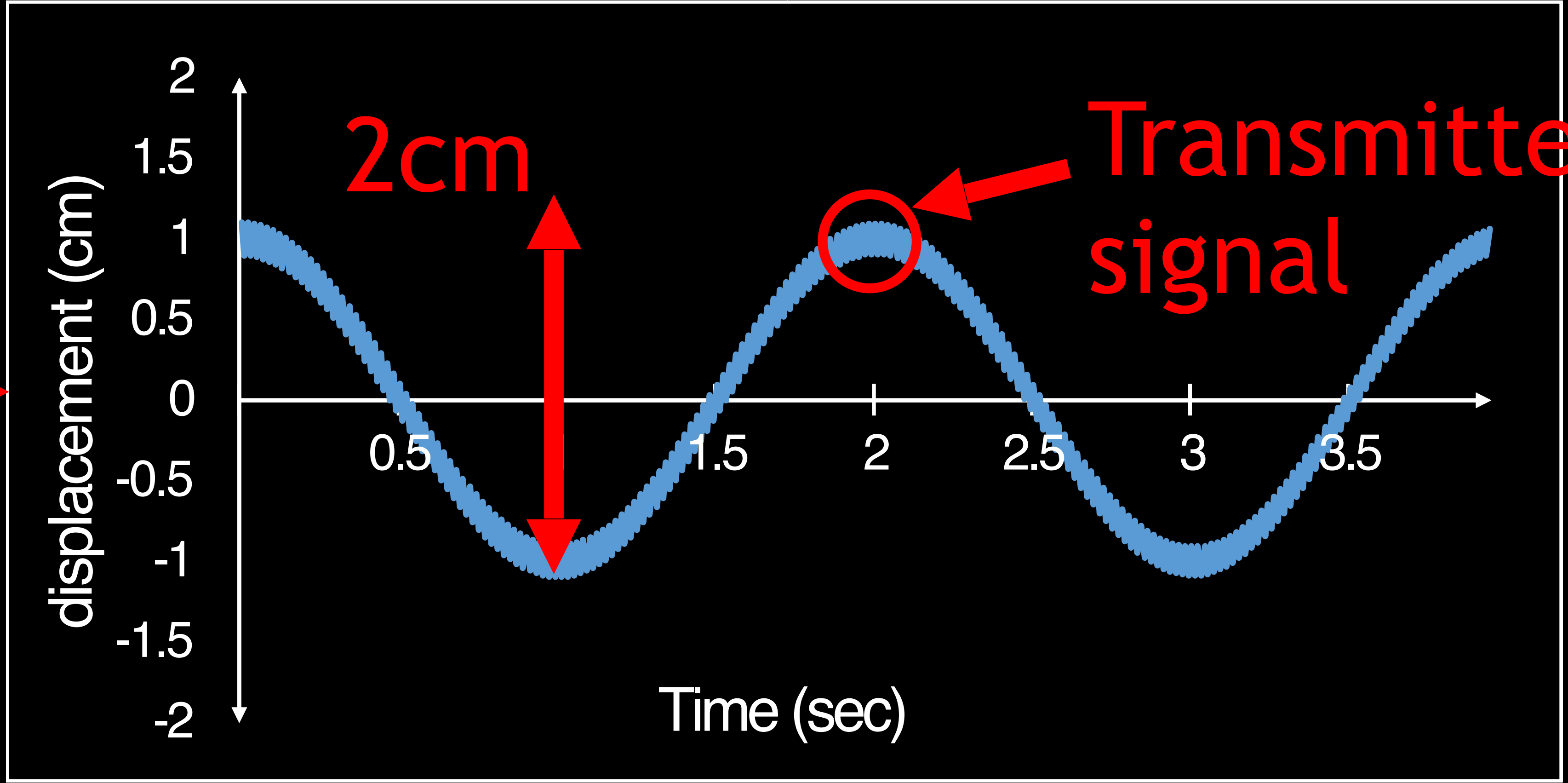


Dealing with Waves



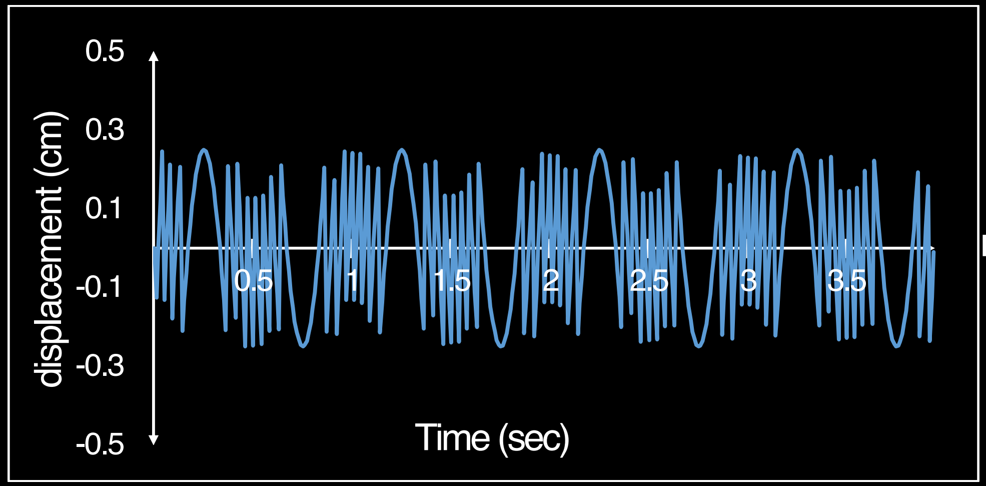
Track & Unwrap

Trend is Water Surface Wave

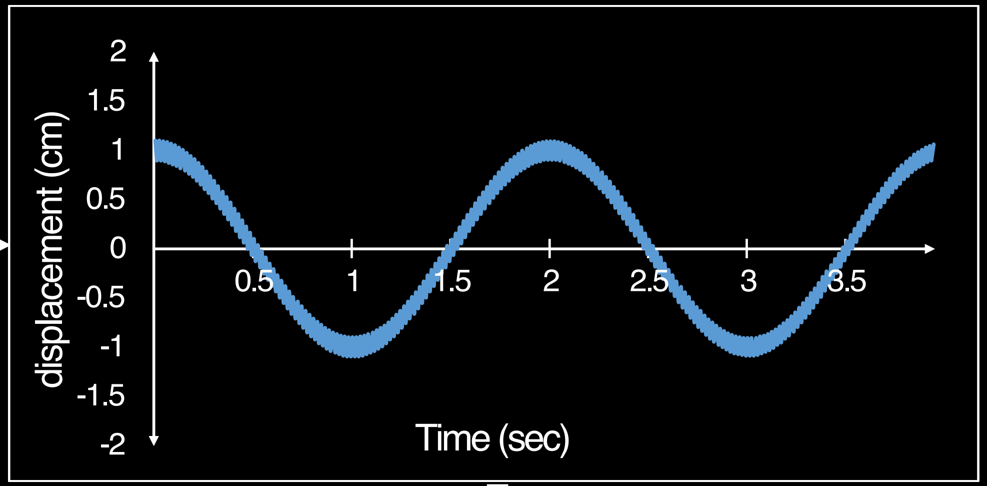


Transmitted signal

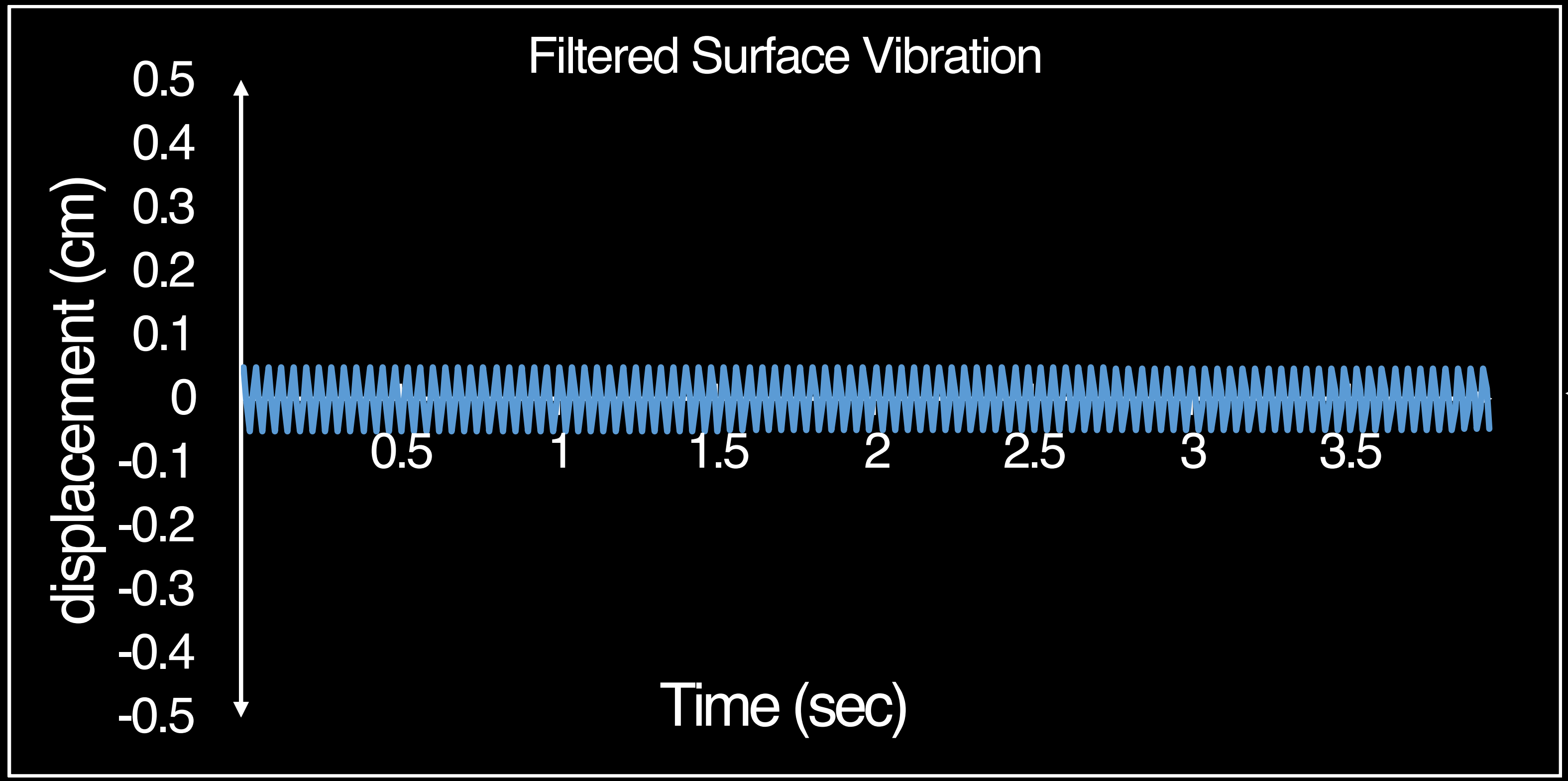
Dealing with Waves



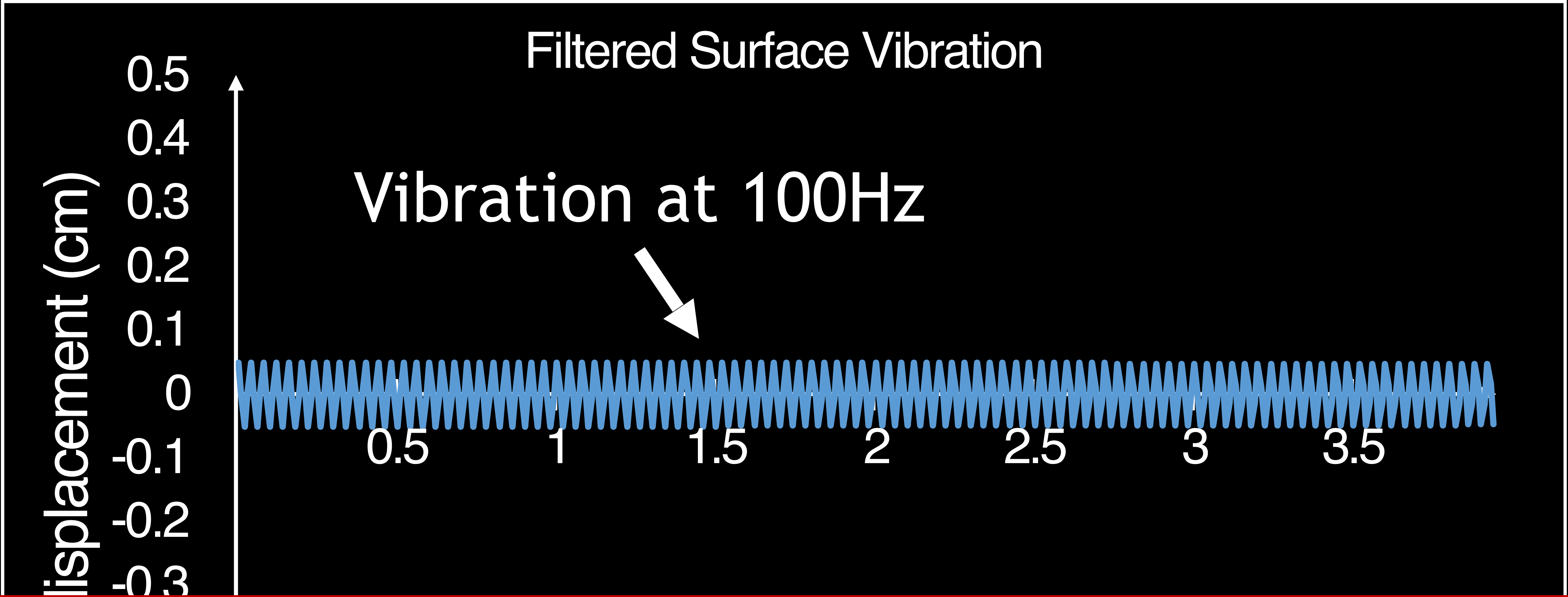
Track & Unwrap



Filter

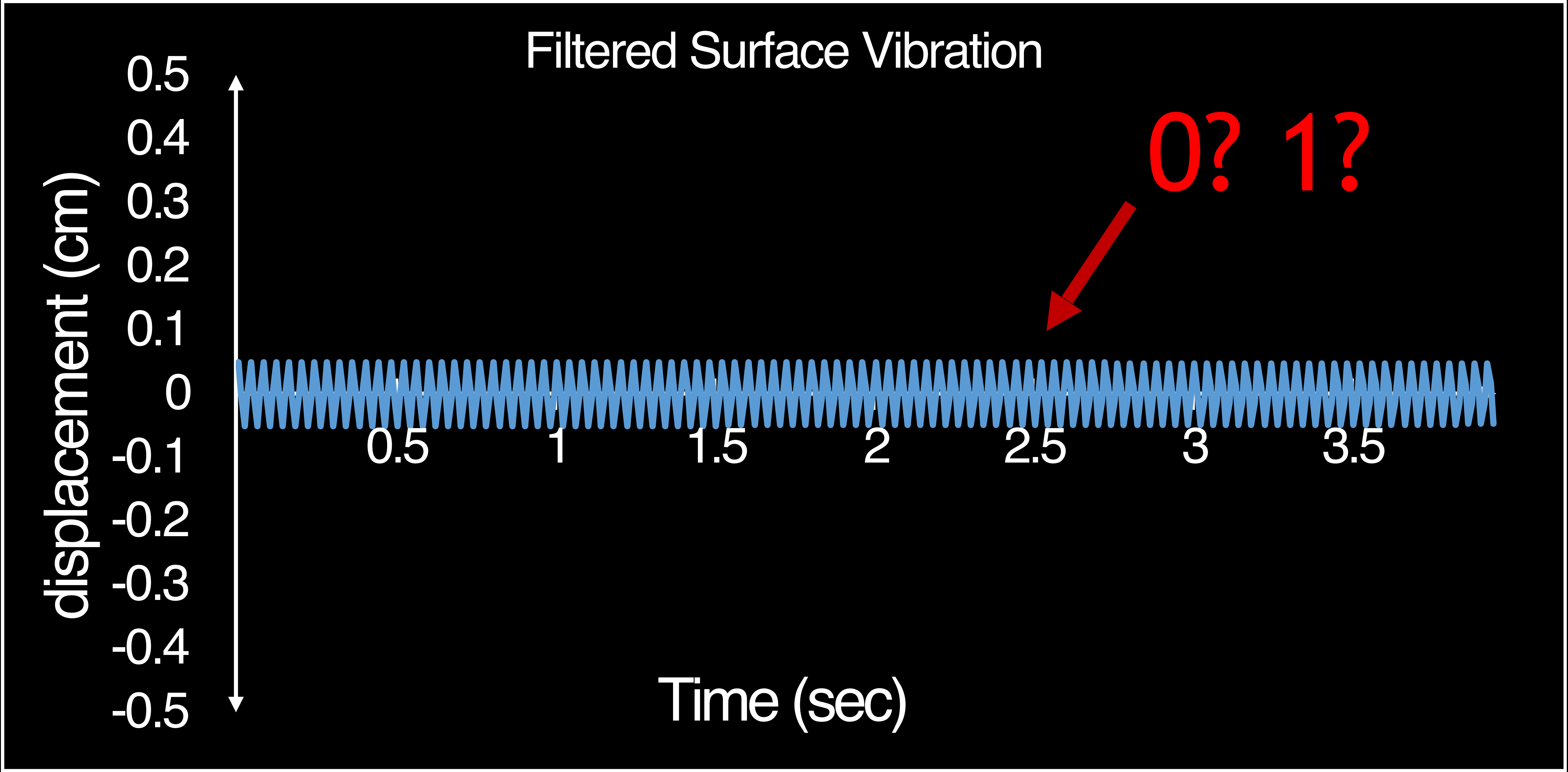


Dealing with Waves



By treating natural surface waves as structured interference, we are able to track and eliminate their impact on our signal

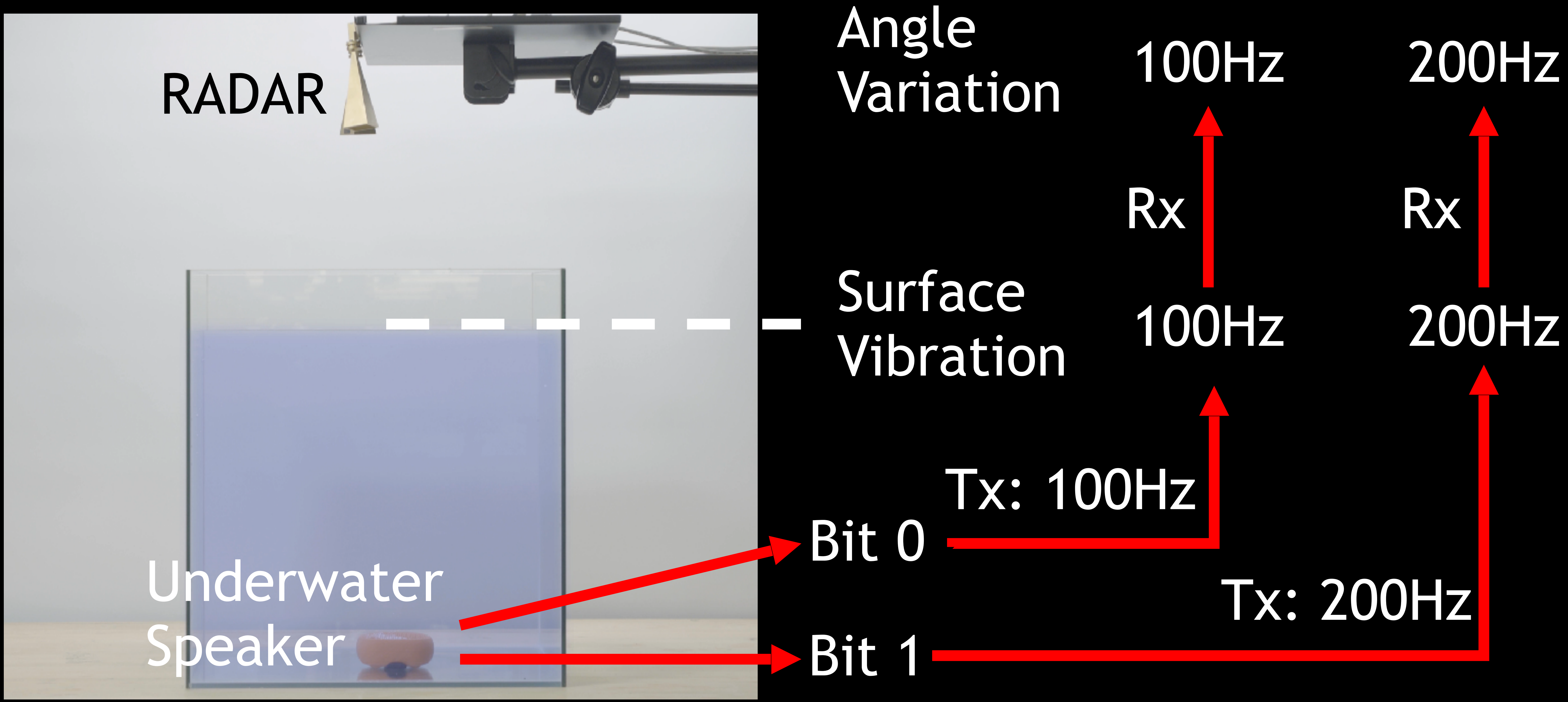
How Can We Decode?



Simple Modulation schemes

ON-OFF keying, FM0/Manchester, FSK

Decoding Information



Standard Modulation Schemes?

The wireless channel

- Mathematics & Physical Interpretation
- Upconversion & Downconversion

Modulation & Demodulation