http://www.mit.edu/~fadel/courses/MAS.s60/index.html

MAS.S60

How to Wirelessly Sense Almost Anything

Lecture 4:
Fundamentals of Wireless Communications

Lecturers

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TA

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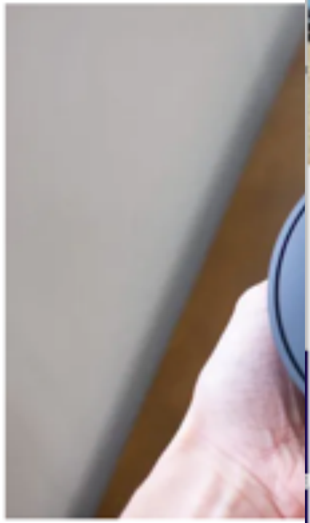
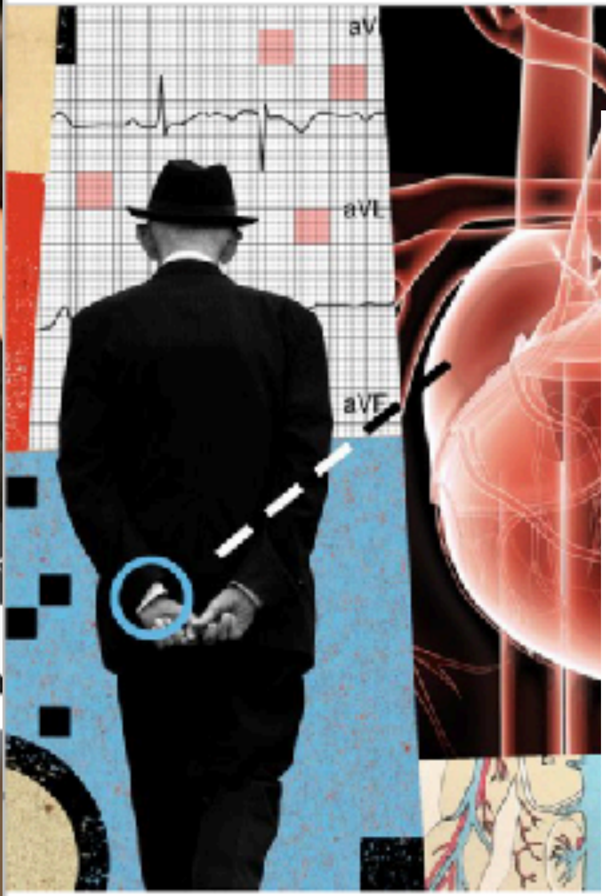
October 1, 2022 7:54am Comment Timi Cartisano

The Magic Leap 2 make… at $3,299



The new iterati… computer.

WSJ



TIM ROBINSON

TECH | FAMILY & TECH: JULIE JARGON

Your Apple Watch… Heart Condition.

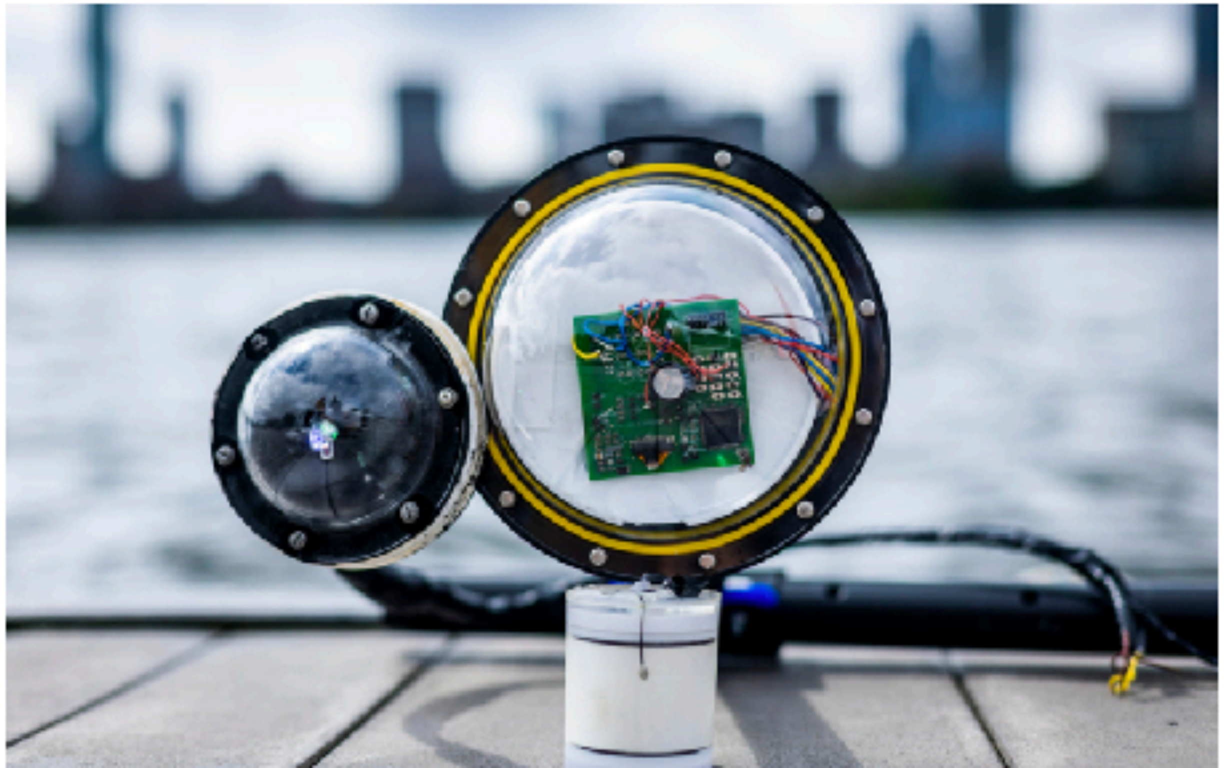
Doctors warn of atrial-fibrillatio… Apple, Fitbit and others. Yes, th… do when you get the alert?

MIT engineers build a battery-free, wireless underwater camera

The device could help scientists explore unknown regions of the ocean, track pollution, or monitor the effects of climate change.

Watch Video

Adam Zewe | MIT News Office
September 26, 2022



How to Wirelessly Sense Almost Anything

sensing the physical world & transmitting data wirelessly

sensing via the wireless signals themselves

So far

How to Wirelessly Sense Almost Anything

sensing the physical world & transmitting data wirelessly

this lecture

sensing via the wireless signals themselves

Objectives of Today's Lecture

Learn the **fundamentals** of communications and emerging technologies for underwater-to-air comms

1. What are the fundamentals of end-to-end wireless communications?
    - The physical, mathematical, engineering, and design fundamentals
    - Why are these systems designed the way they are
2. How can we use wireless sensing *for* communications? (converse of last 2 lectures)
3. How do underwater-to-air communication systems work?

How can we send sensed information from underwater to outside the ocean?

Underwater-to-Air Comm Applications

Submarine-Airplane Communication

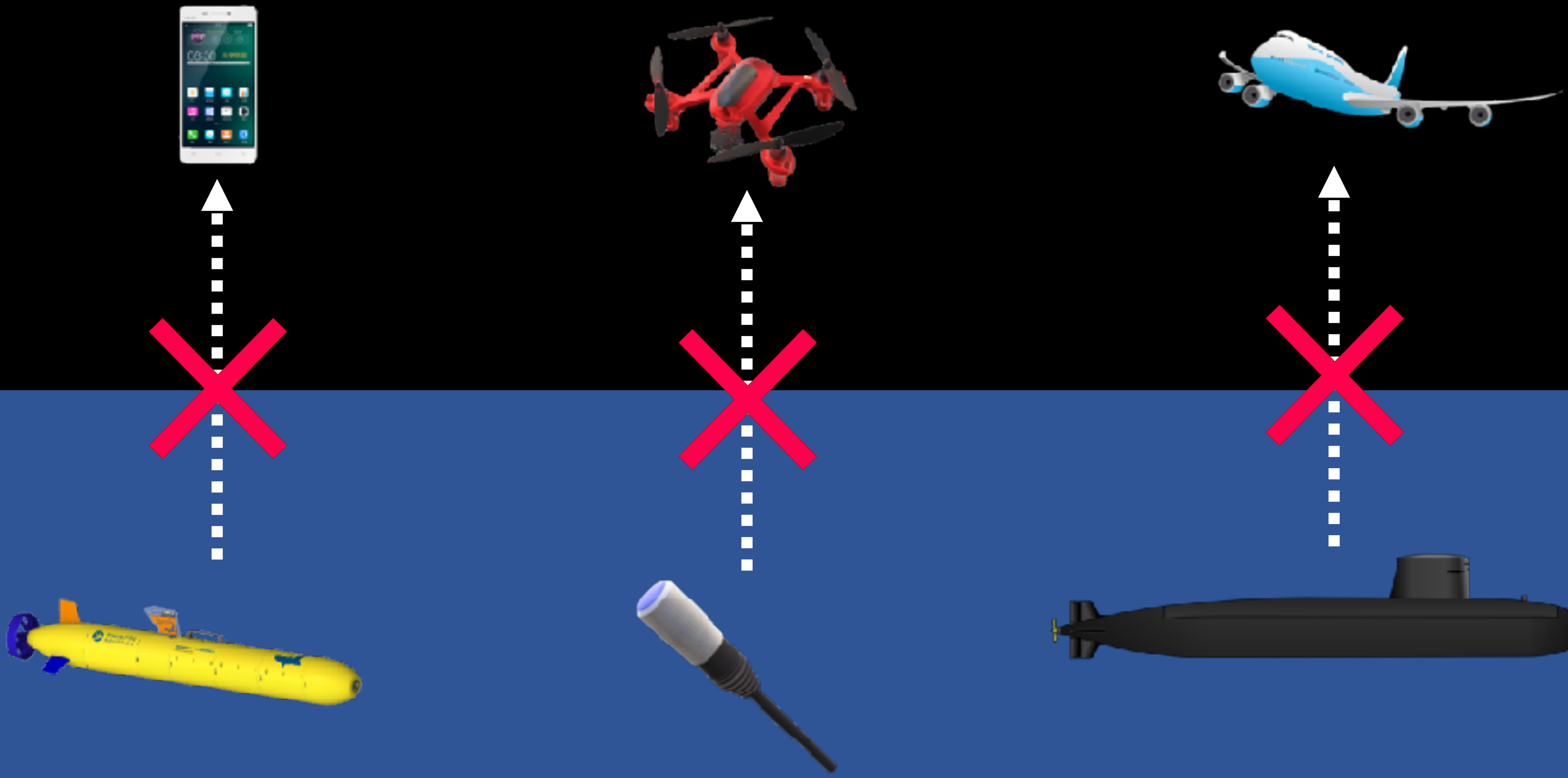
Finding Missing Airplanes

Ocean Scientific Exploration

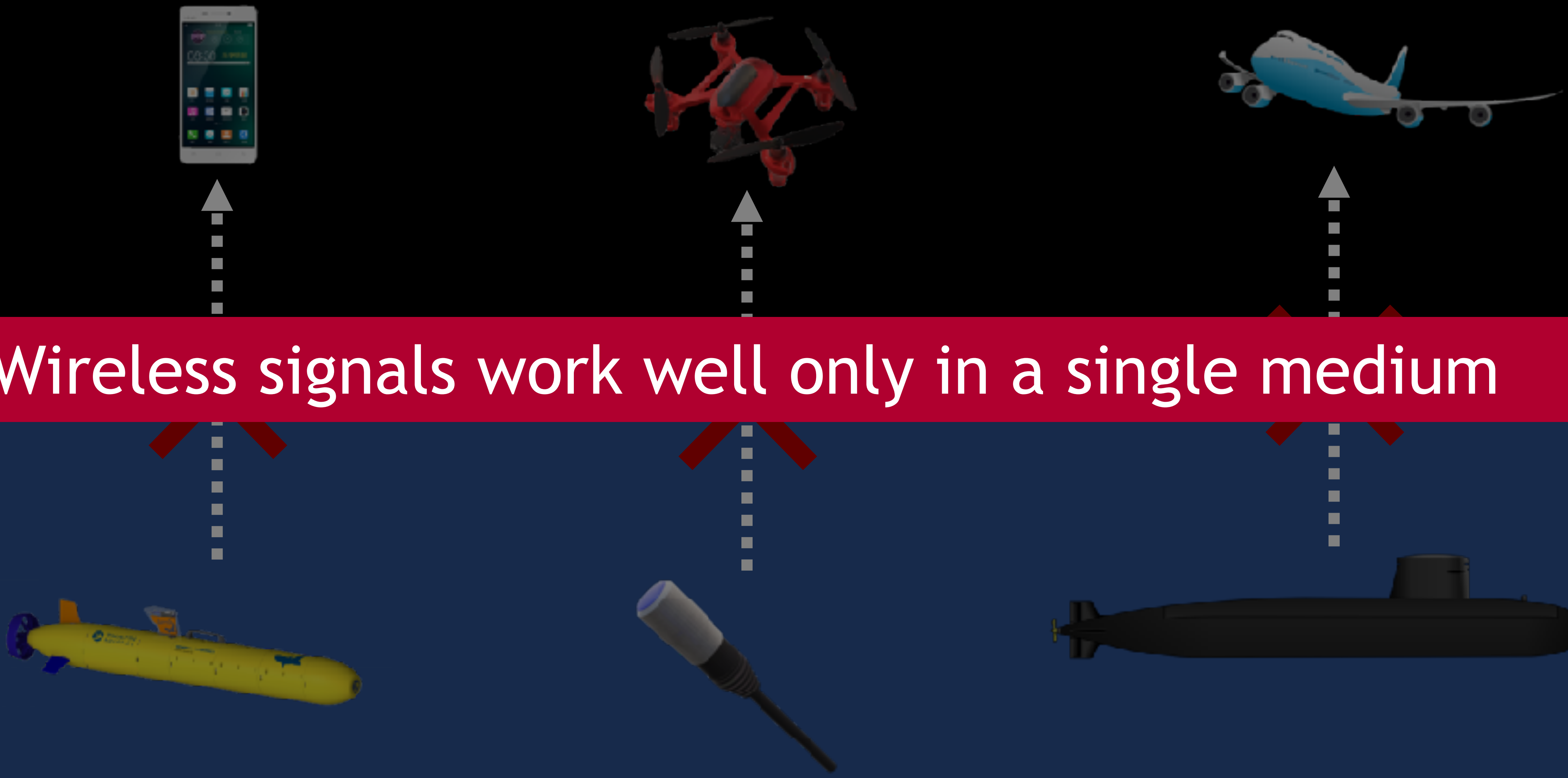
Underwater-to-Air Comm Applications

Why is it difficult?

Direct Underwater-Air Communication is Infeasible



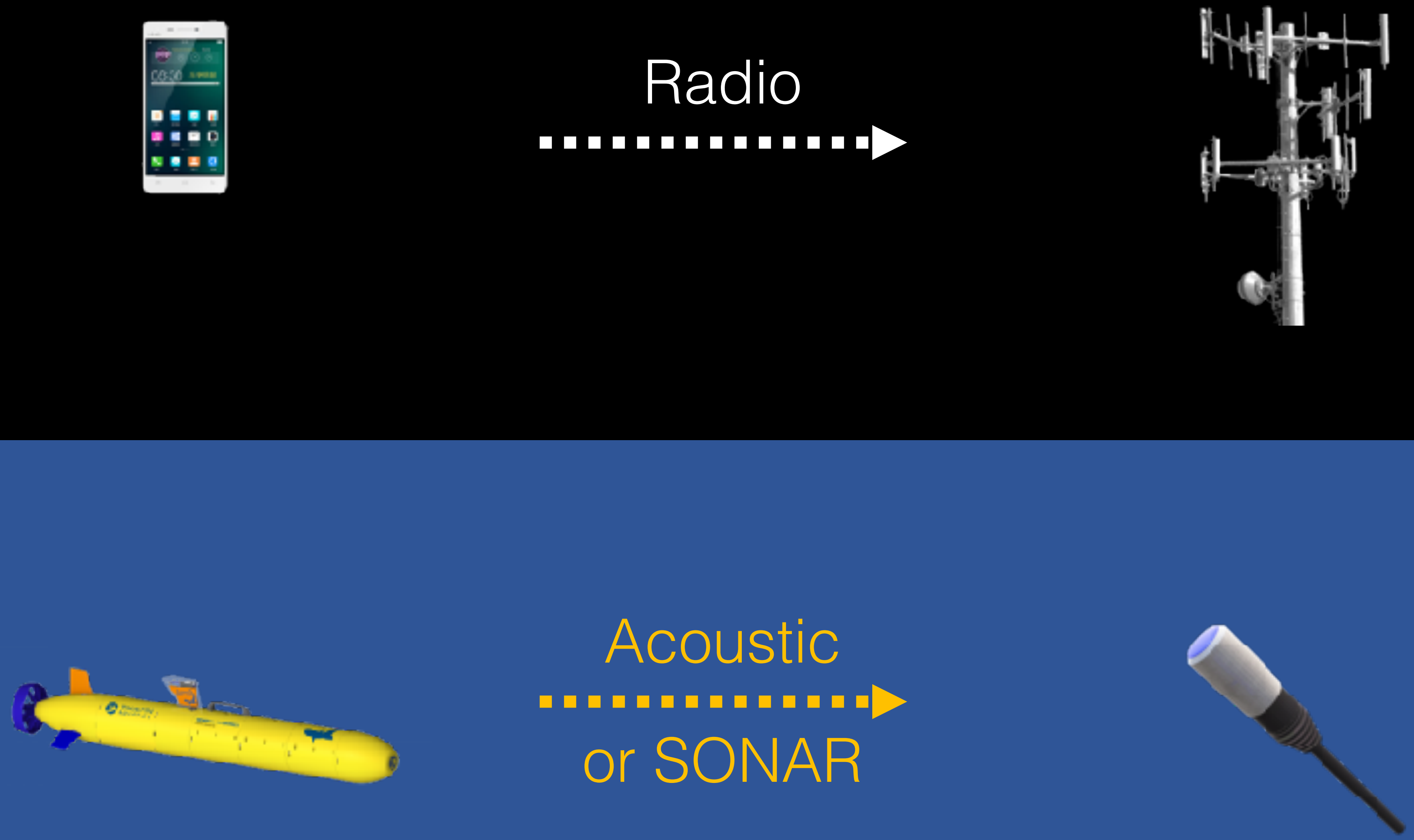
Direct Underwater-Air Communication is Infeasible



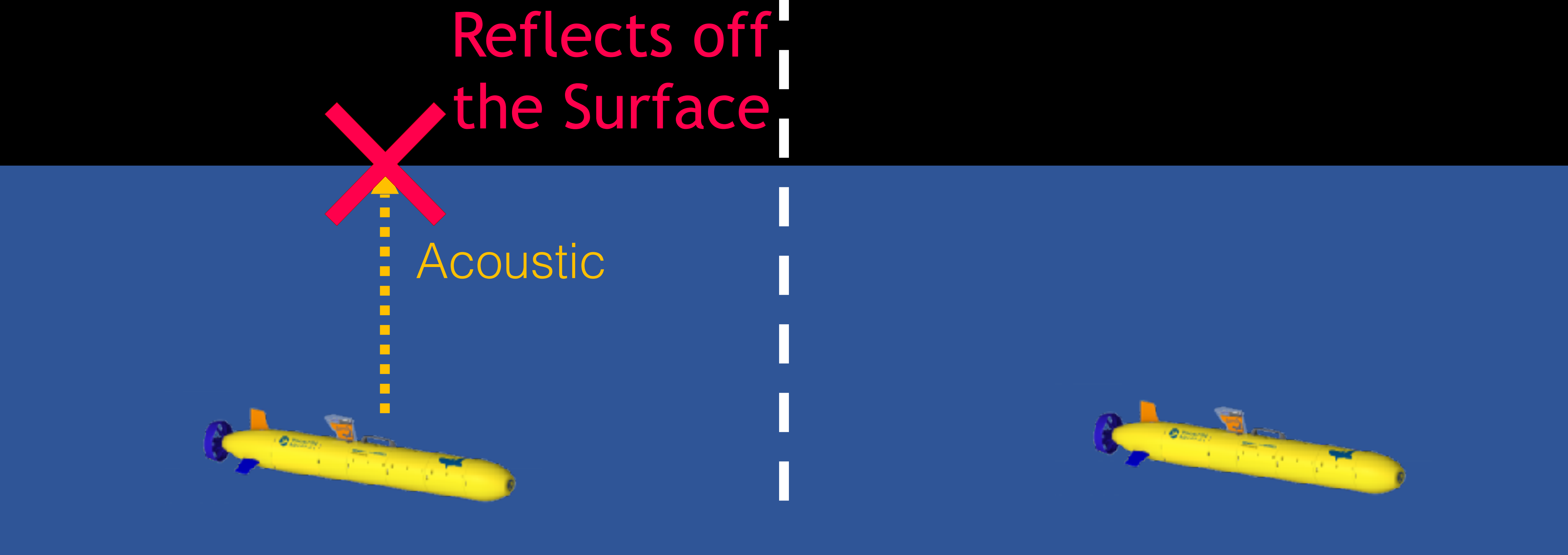
Wireless signals work well only in a single medium

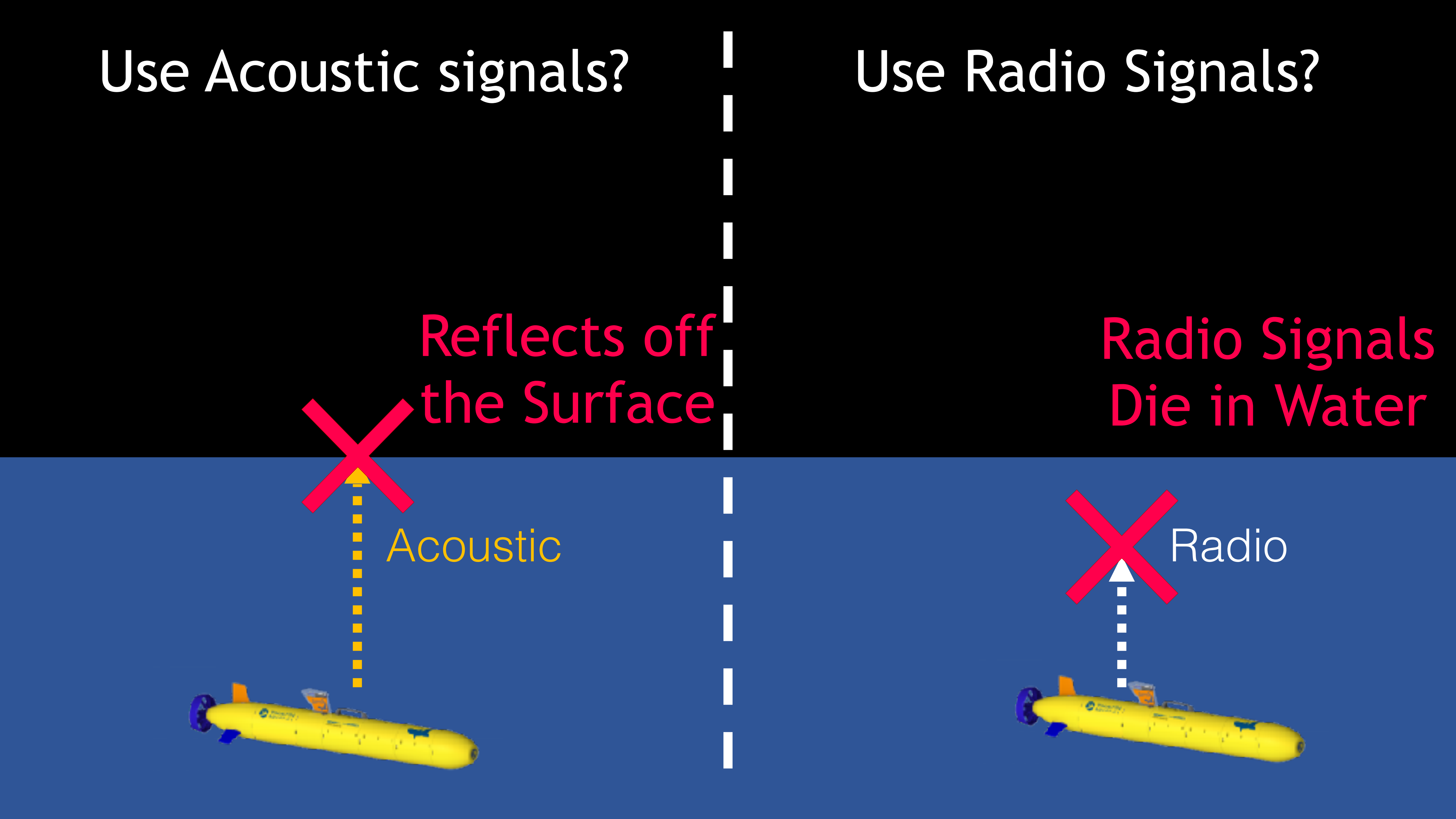
Wireless Signals Work Well Only in a Single Medium

Wireless Signals Work Well Only in a Single Medium



Use Acoustic signals?

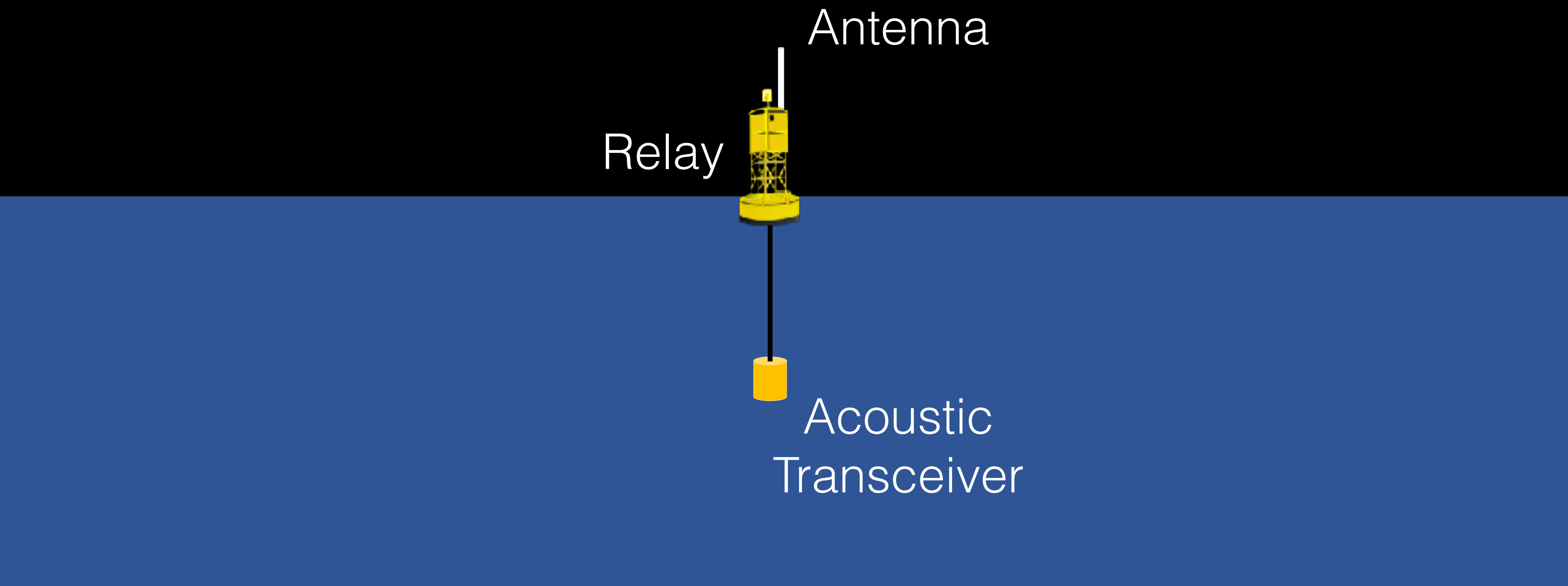



Use Acoustic signals?
Use Radio Signals?
Reflects off the Surface
Radio Signals Die in Water
Acoustic
Radio

What are today’s approaches for solving this problem?

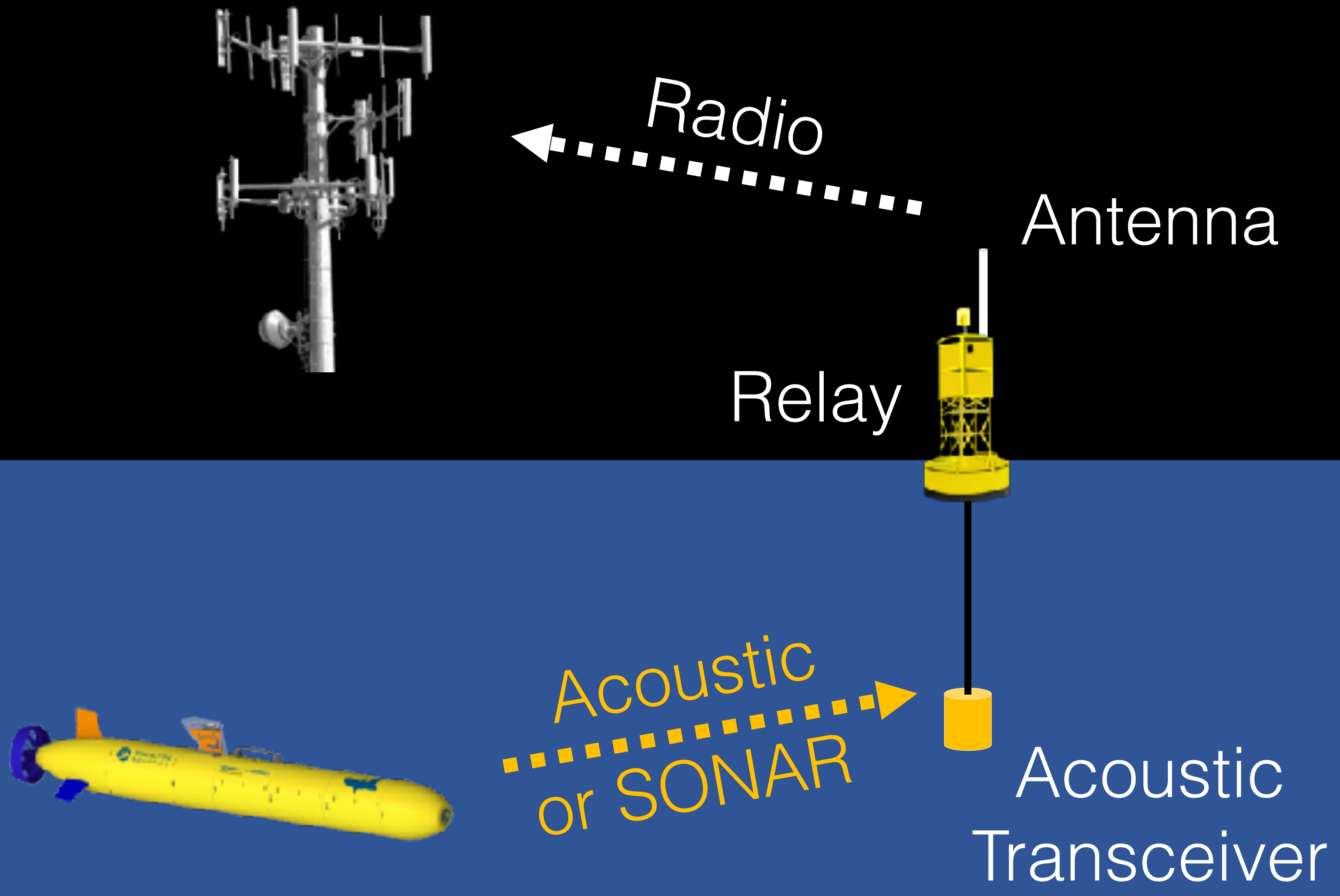
Approach #1: Relay Nodes

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



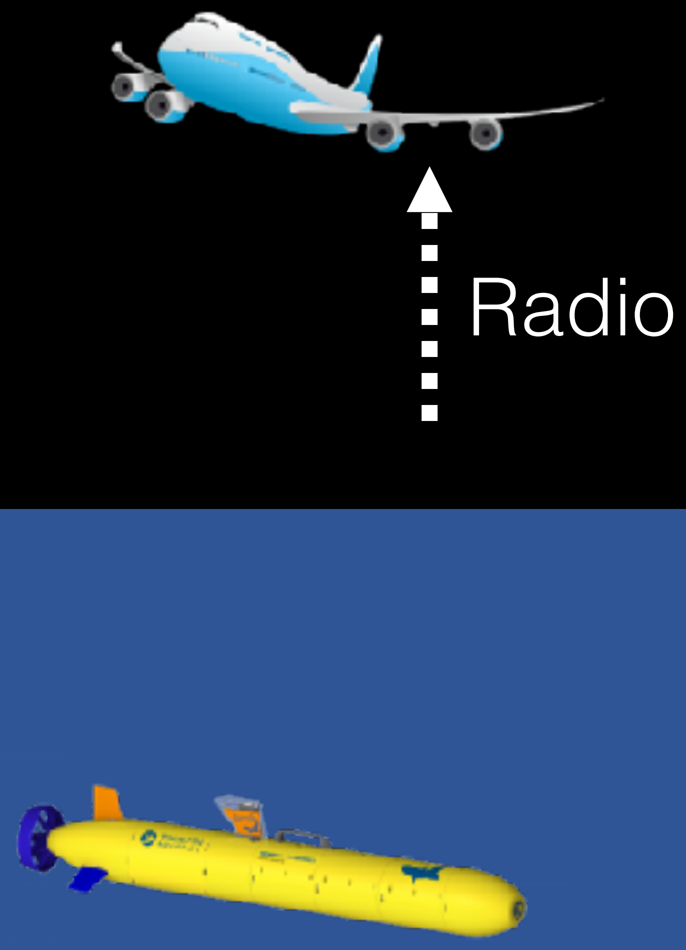
Approach #1: Relay Nodes

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



Approach #2: Surfacing

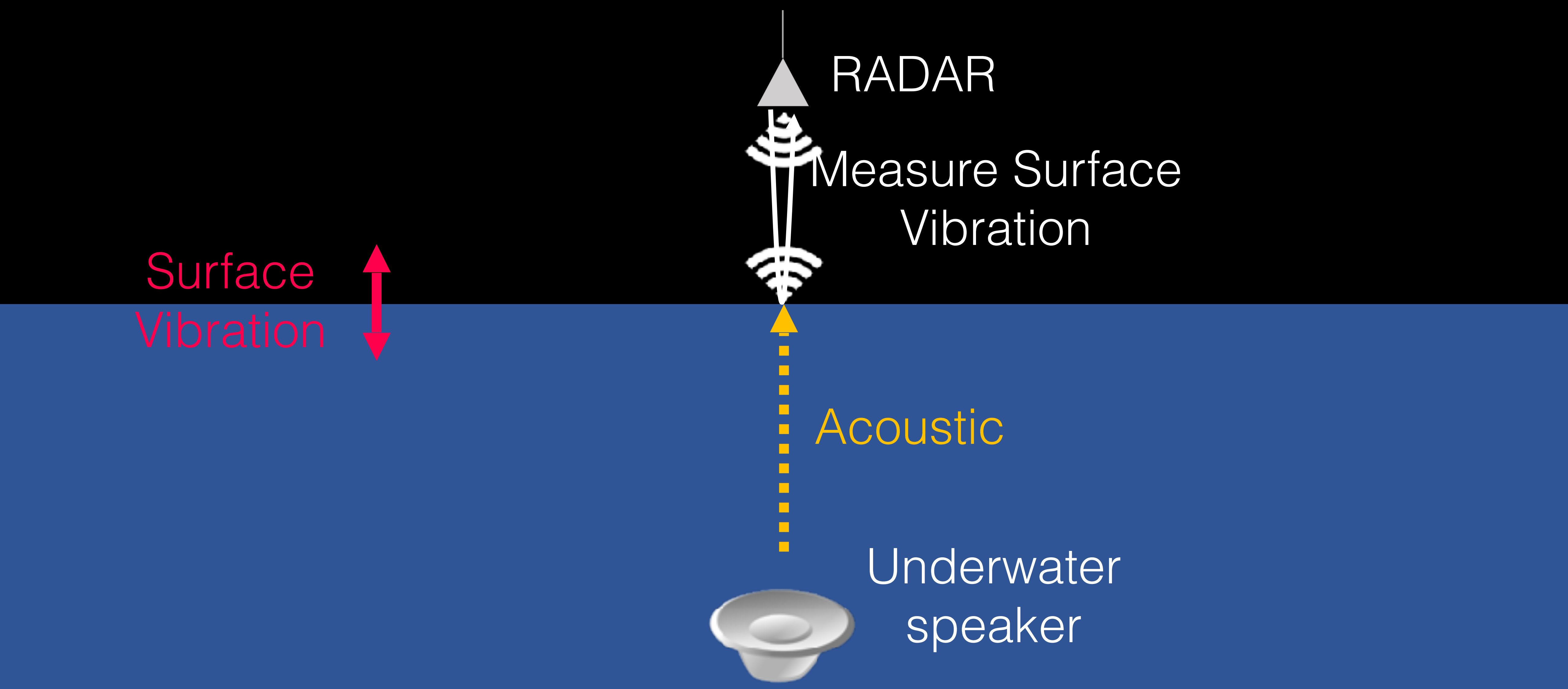
[ICRA’06, MOBICOM’07, OCEANS’10, ICRA’12]



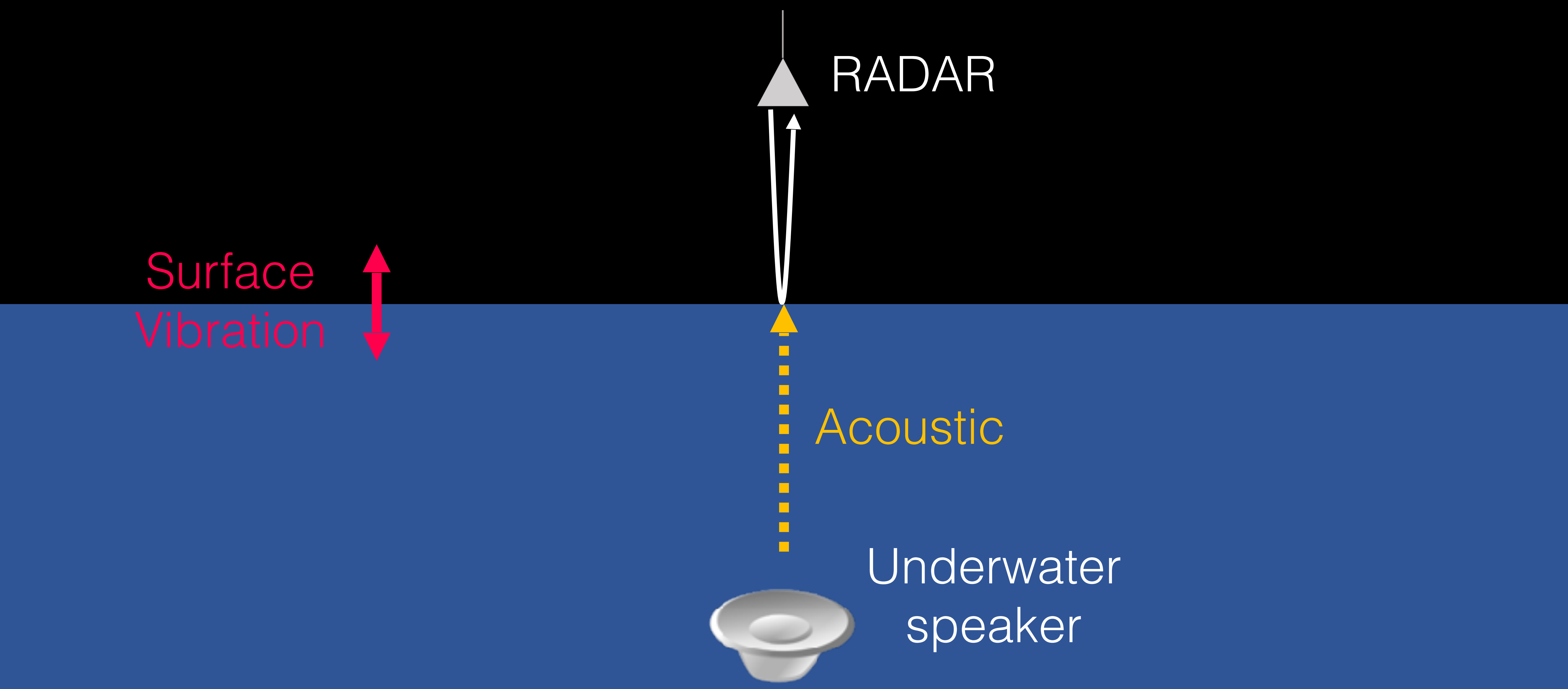
Technology that Enables Compact Sensors to Wirelessly Communicate Across the Water-Air Boundary

How does it work?

Technology that Enables Compact Sensors to Wirelessly Communicate Across the Water-Air Boundary



Translational Acoustic RF Communication (TARF)



Translational Acoustic RF Communication

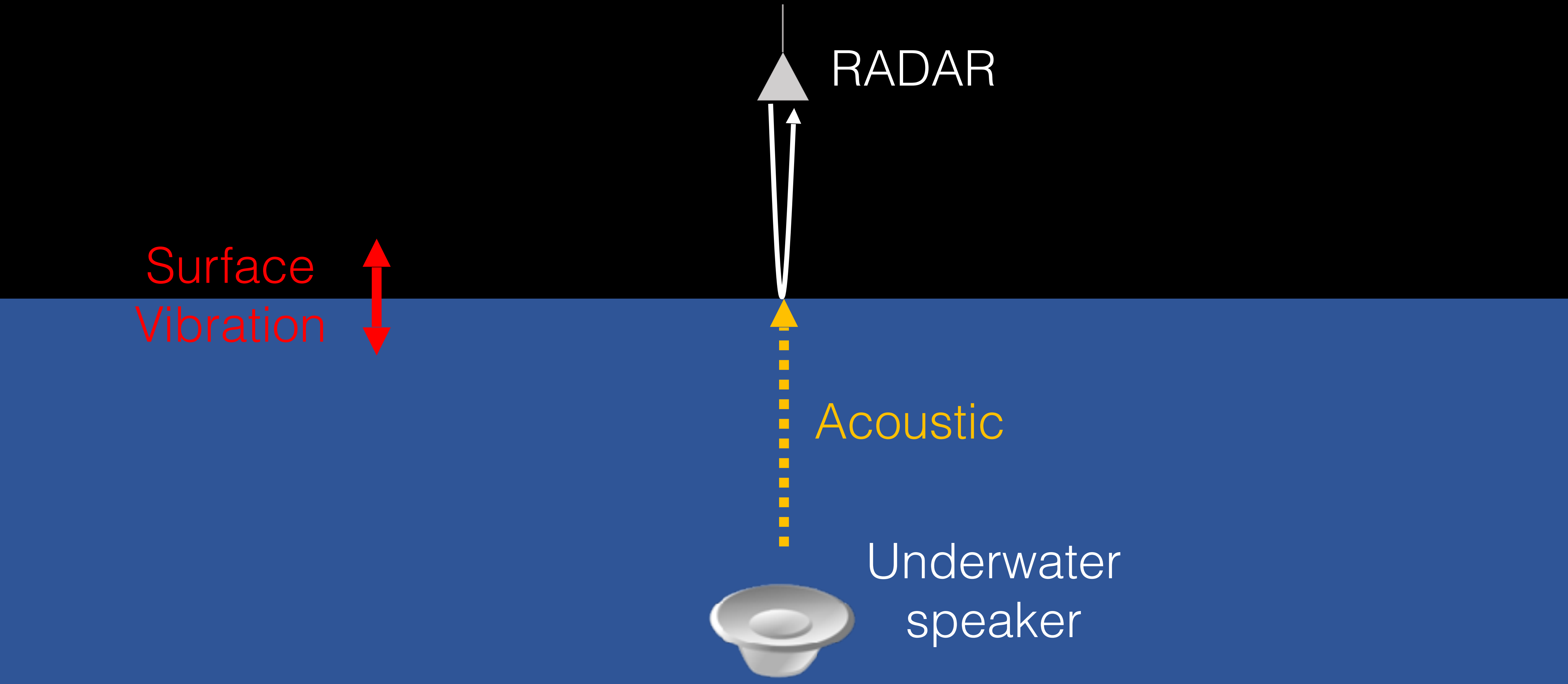
First technology that enables wireless communication across water-air interface

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

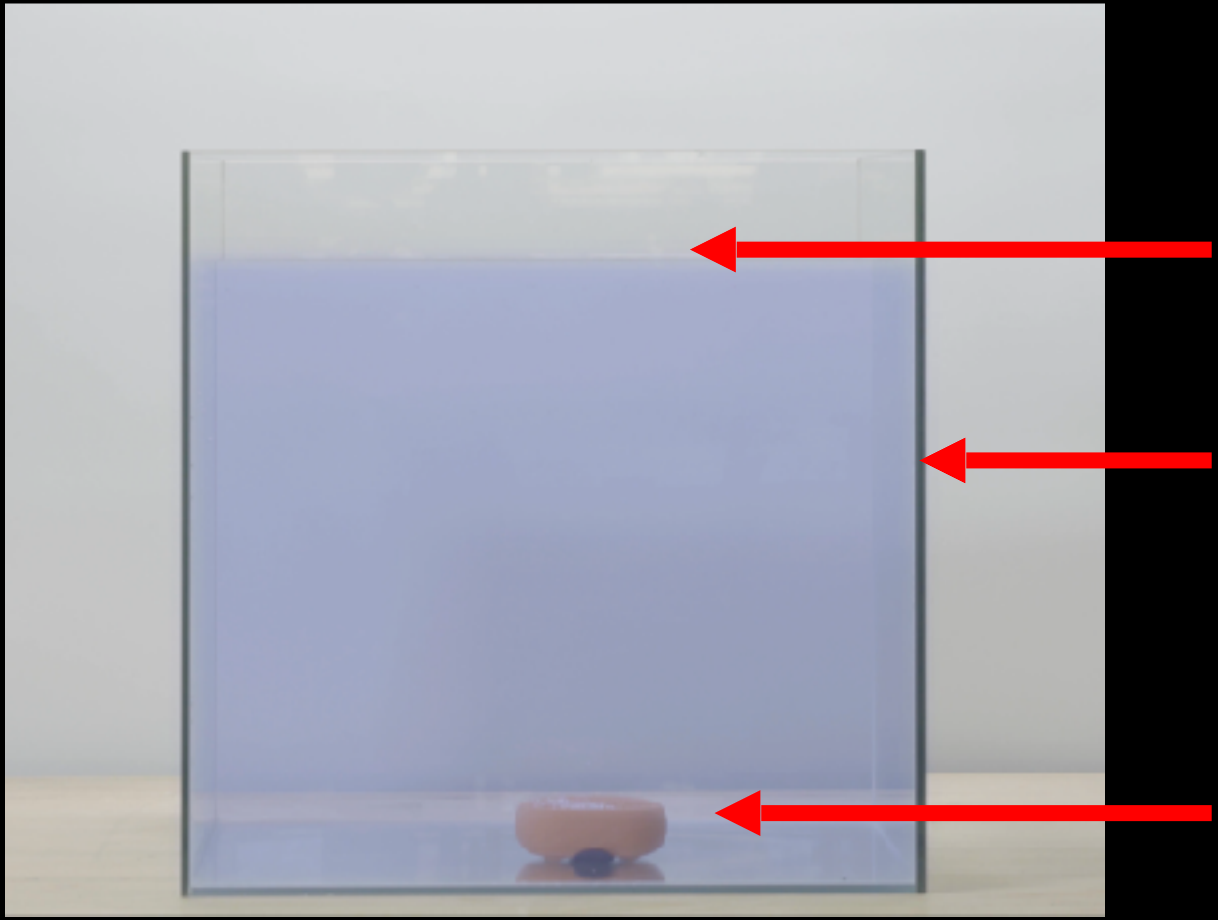
Key Idea



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

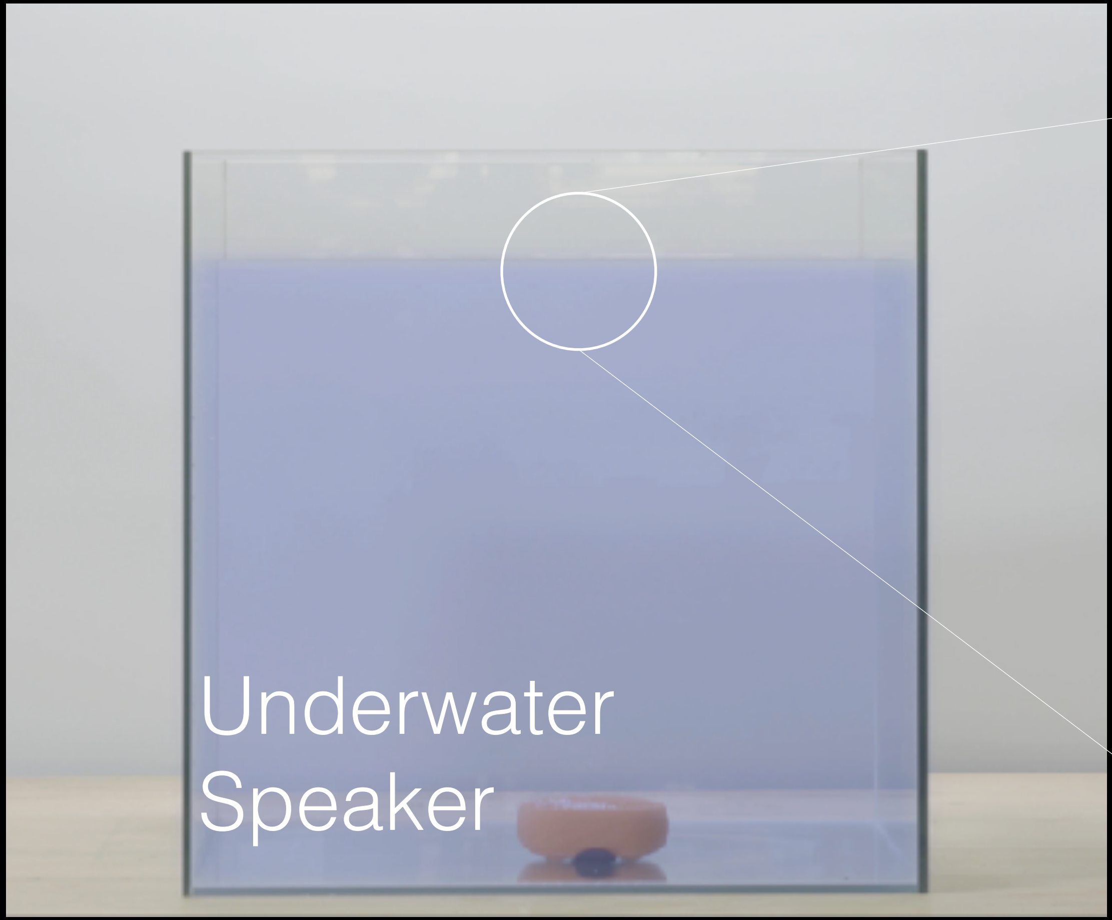
Recording the Surface Vibration

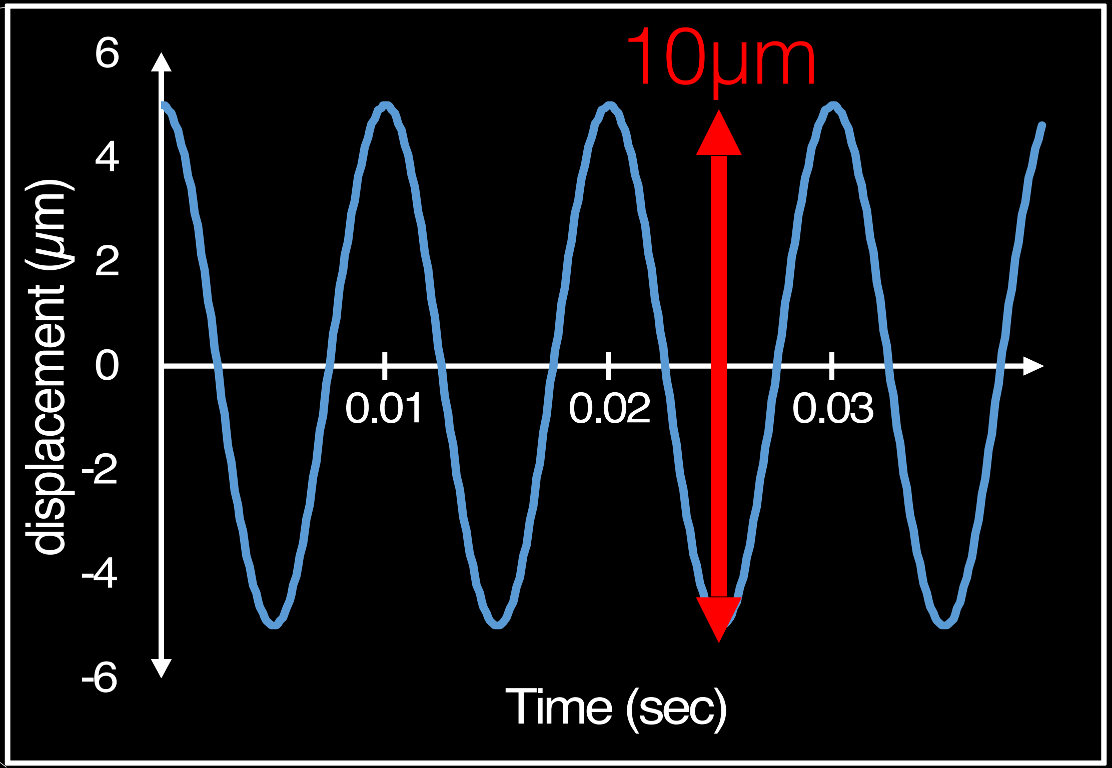
Experiment: Transmit Acoustic Signals at 100Hz



Recording the Surface Vibration

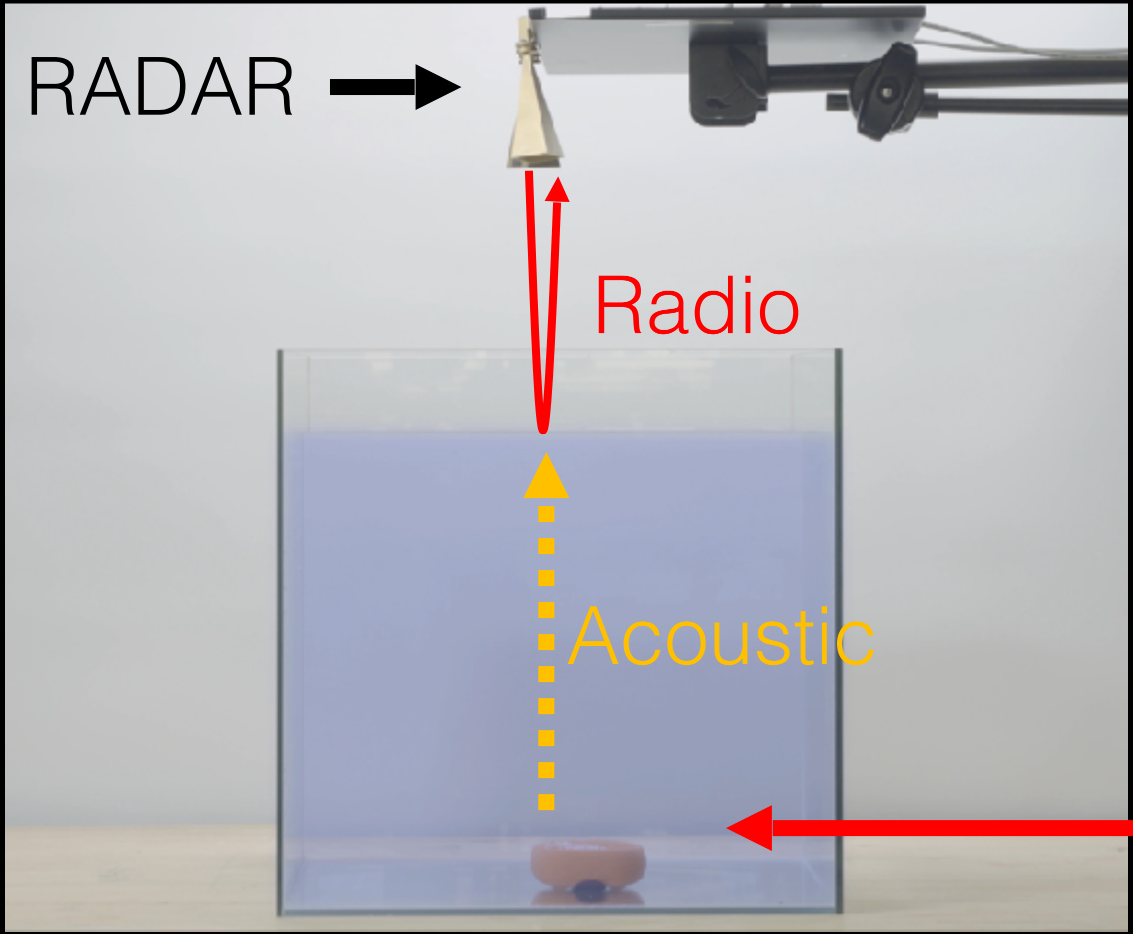
Experiment: Transmit Acoustic Signals at 100Hz





How Can We Sense Microscale Vibration?

Idea: Use RADAR to measure the surface vibration



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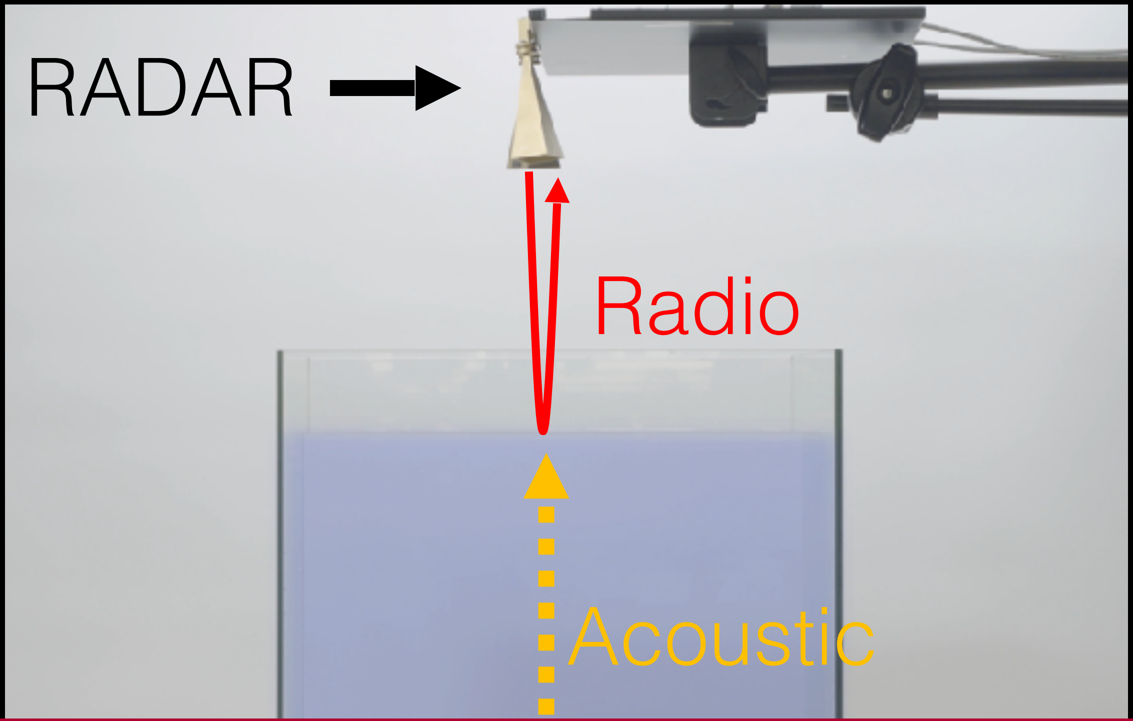
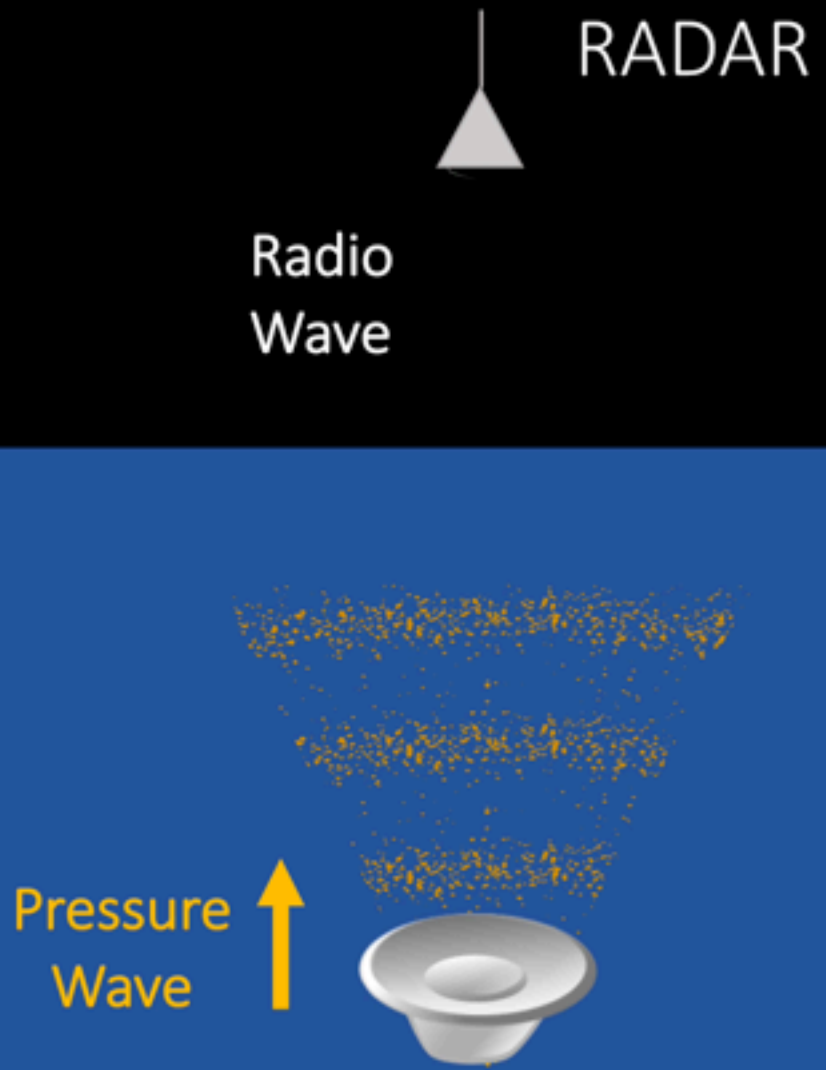
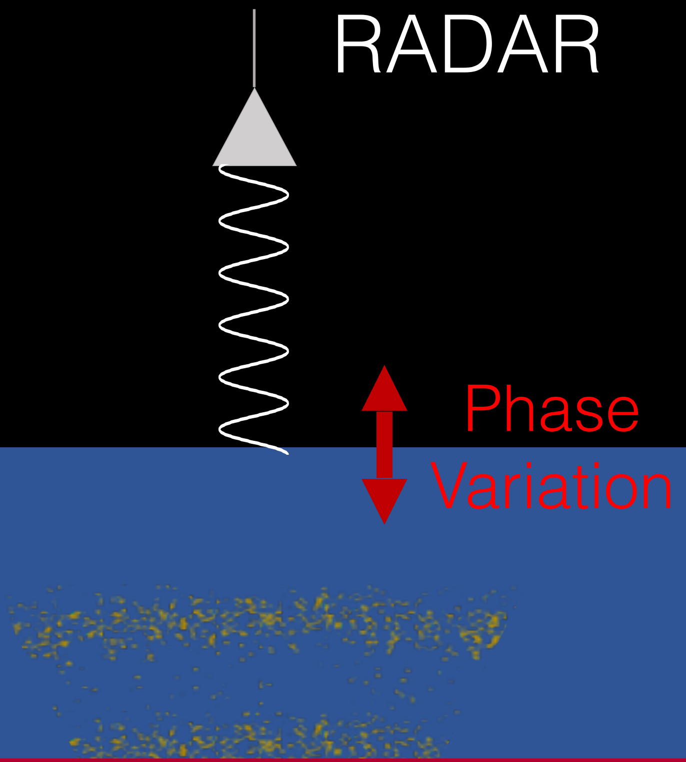


<u>Problem:</u> Measuring micrometer vibrations requires 100s of THz of bandwidth → Impractical & Costly

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



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



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

displacement: 10μm

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

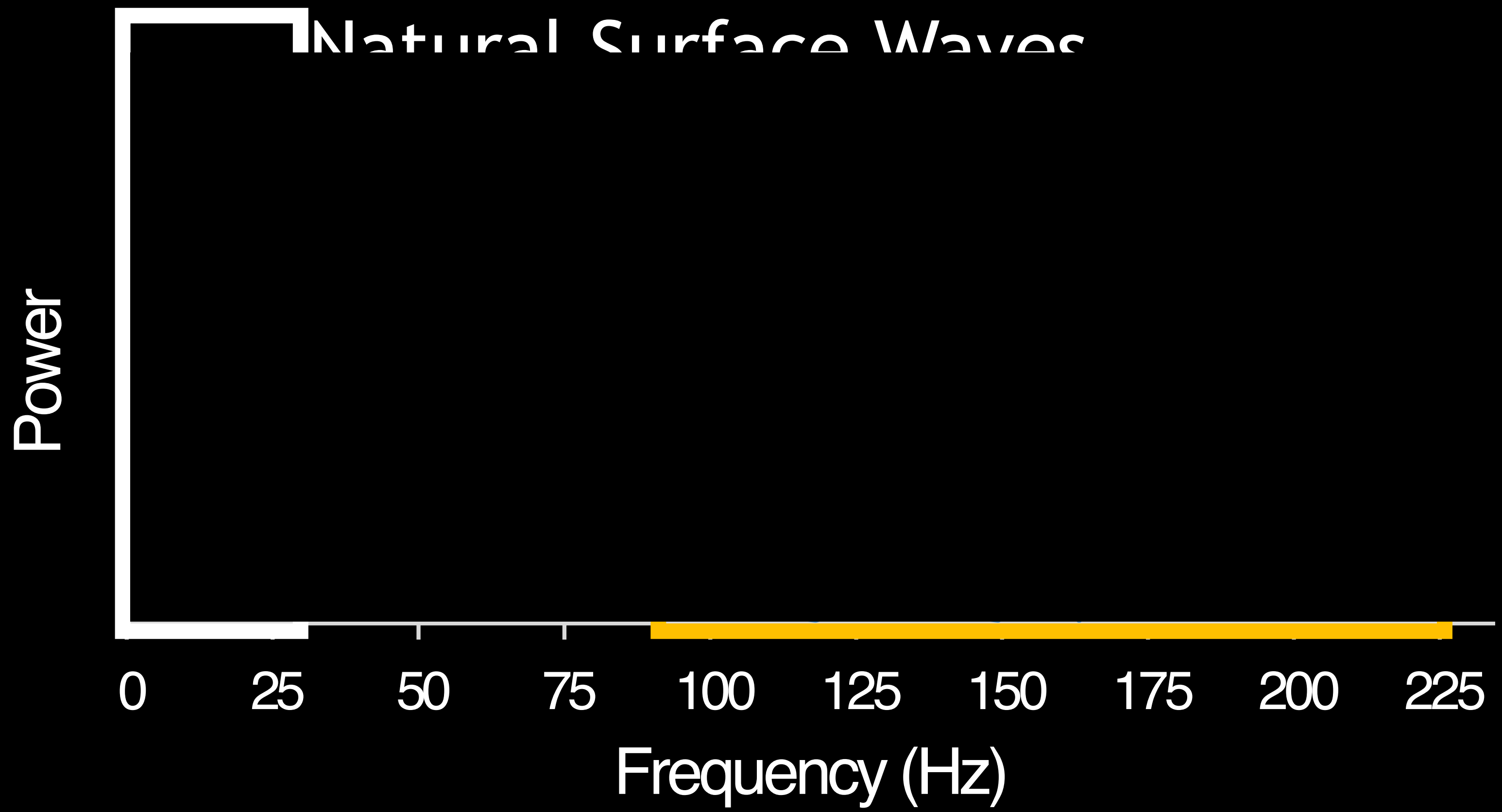
↓

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

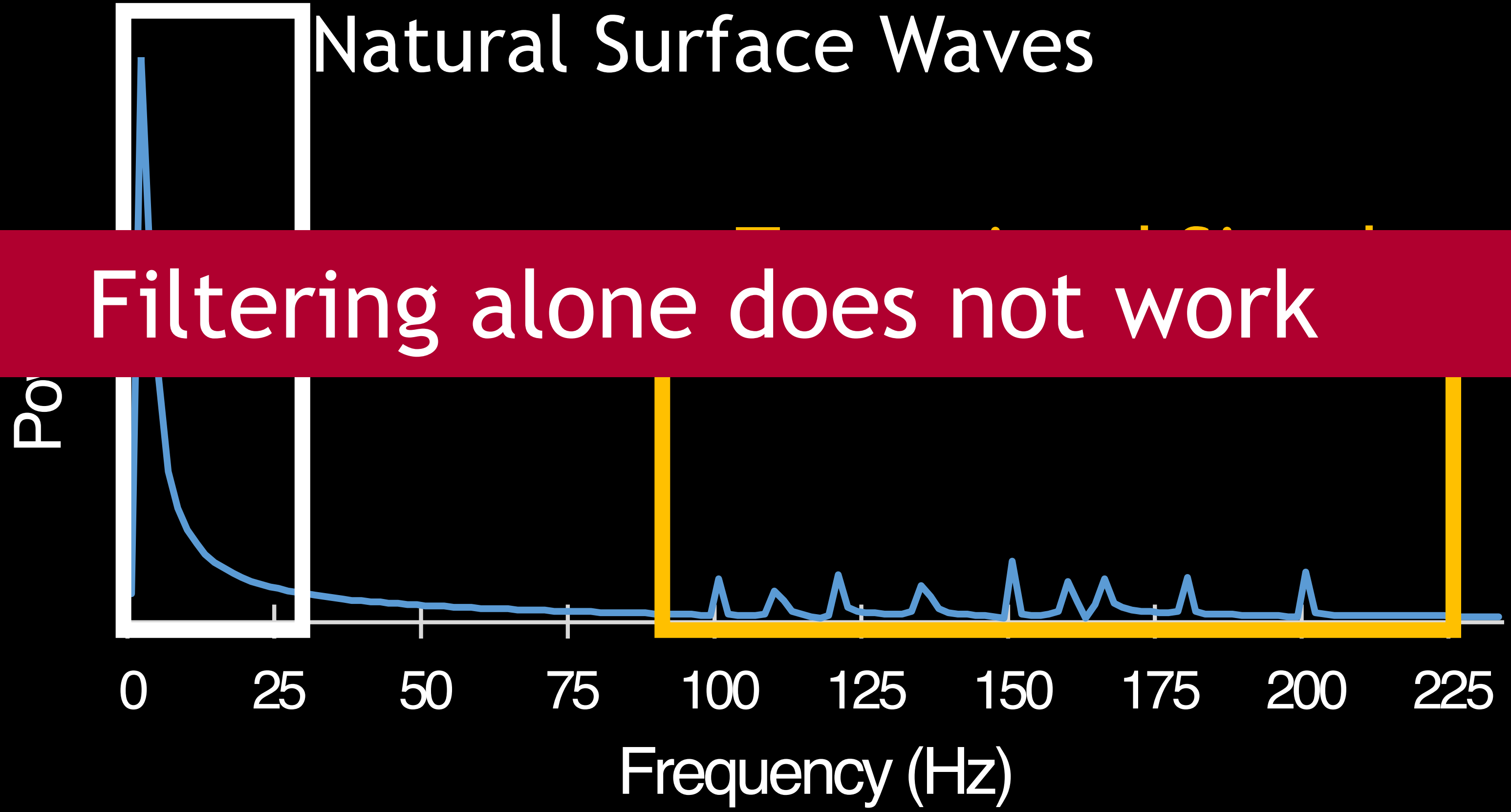
Natural Surface Waves Can Be Treated as Structured Interference and Filtered Out

	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

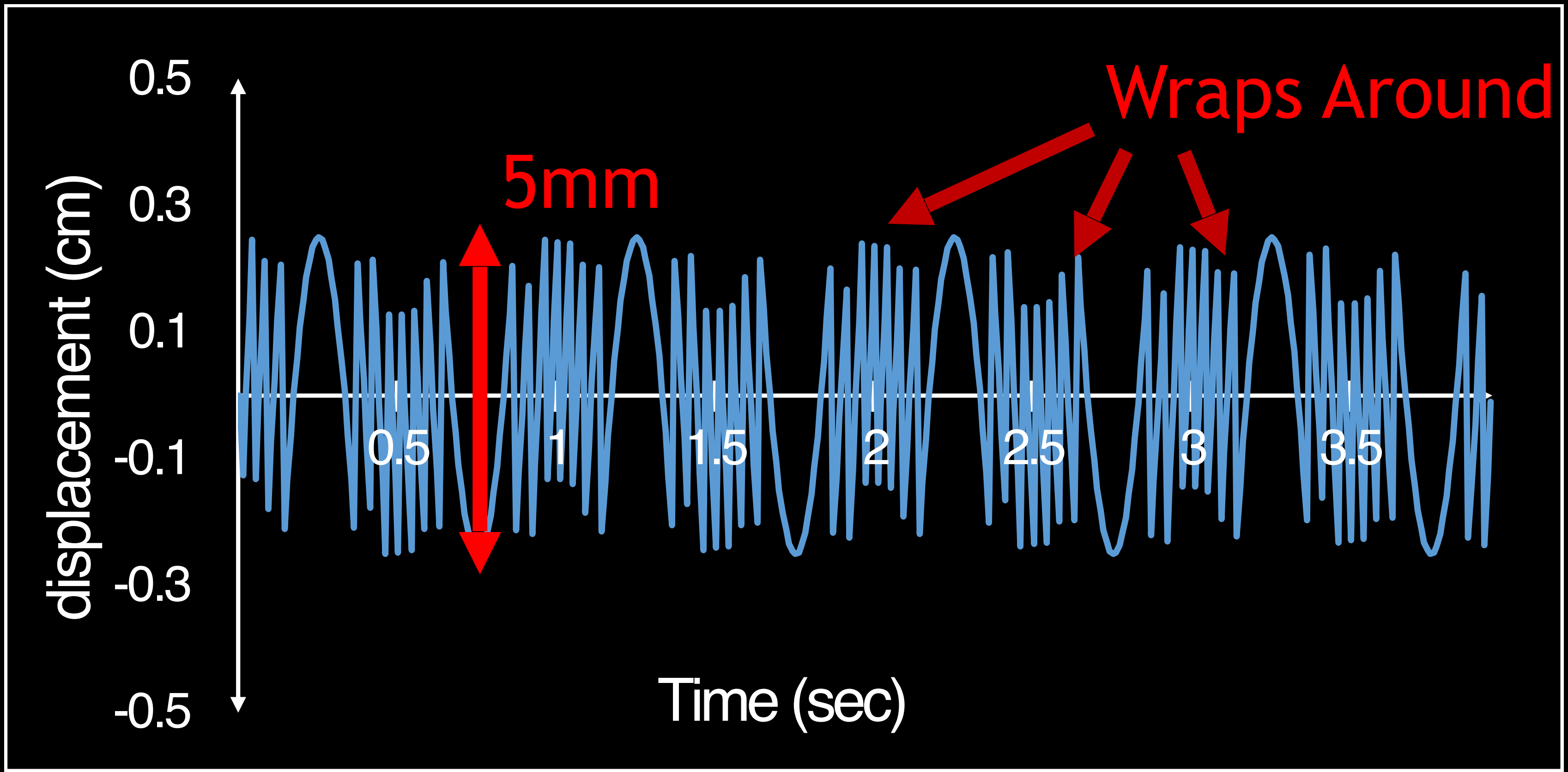
$$Angle = 360 \times \frac{displacement}{wavelength}$$

Dealing with Waves

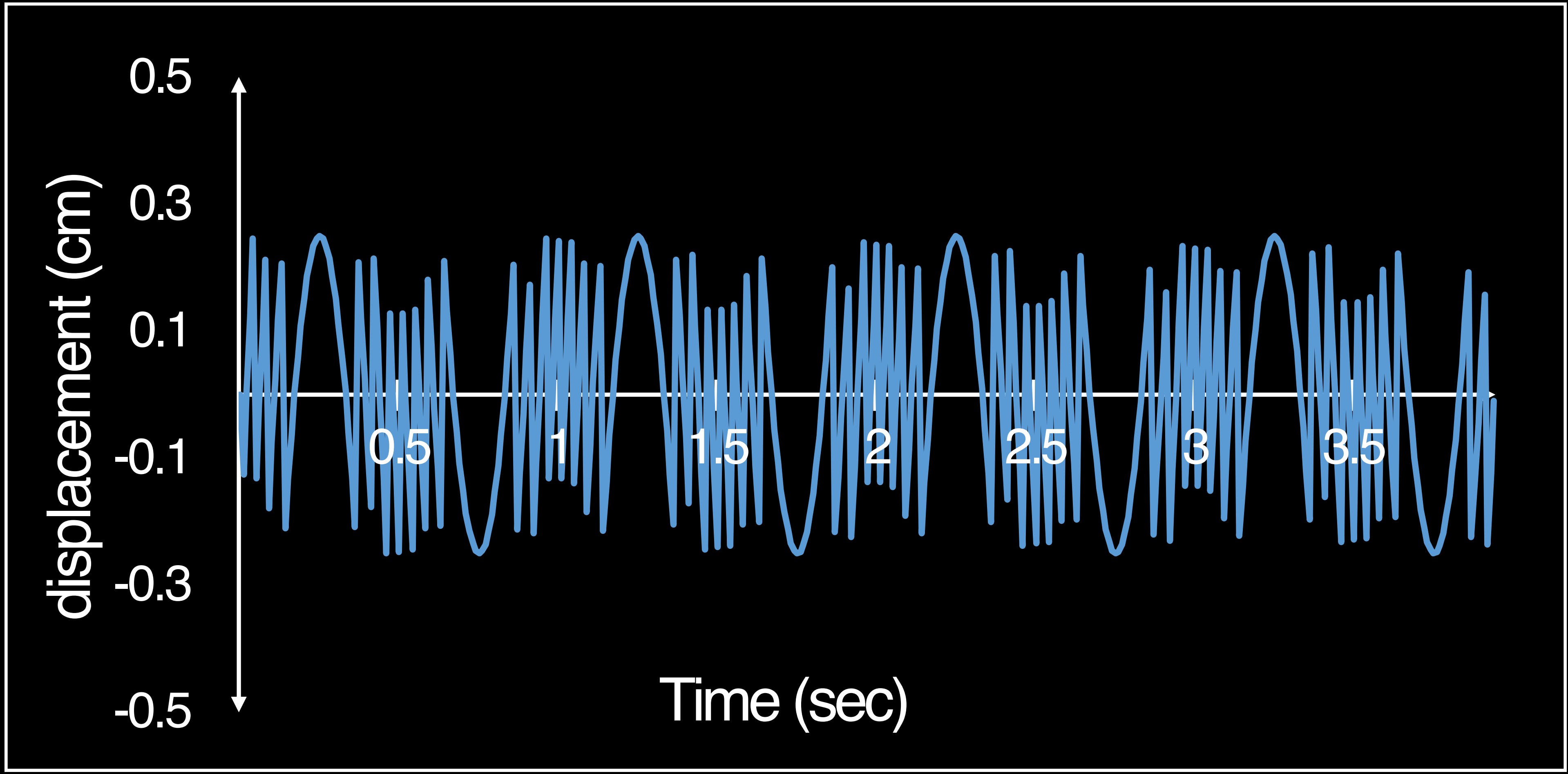
$$Angle = 360 \times \frac{displacement}{wavelength} \mod 360$$

Dealing with Waves

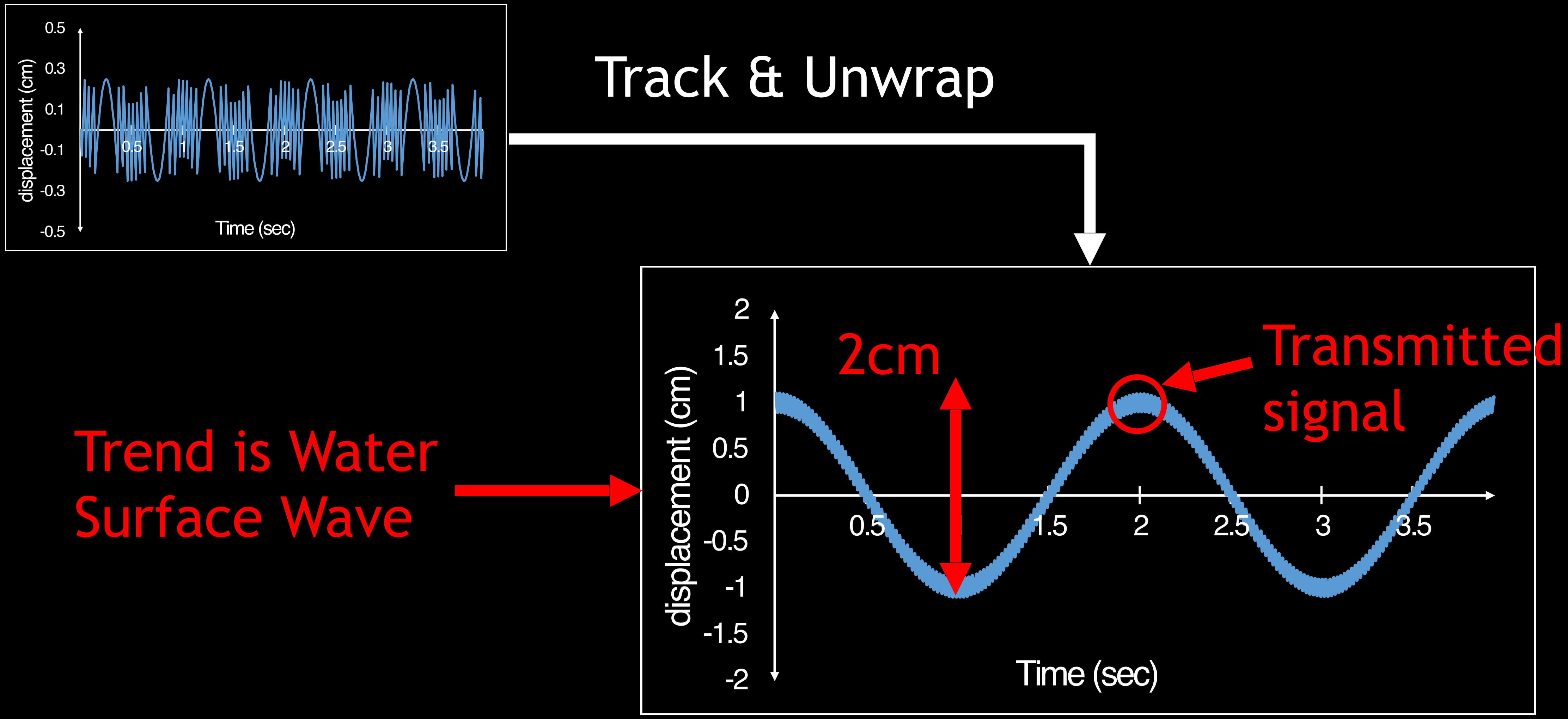
$$Angle = 360 \times \frac{displacement}{wavelength} \; mod\ 360$$



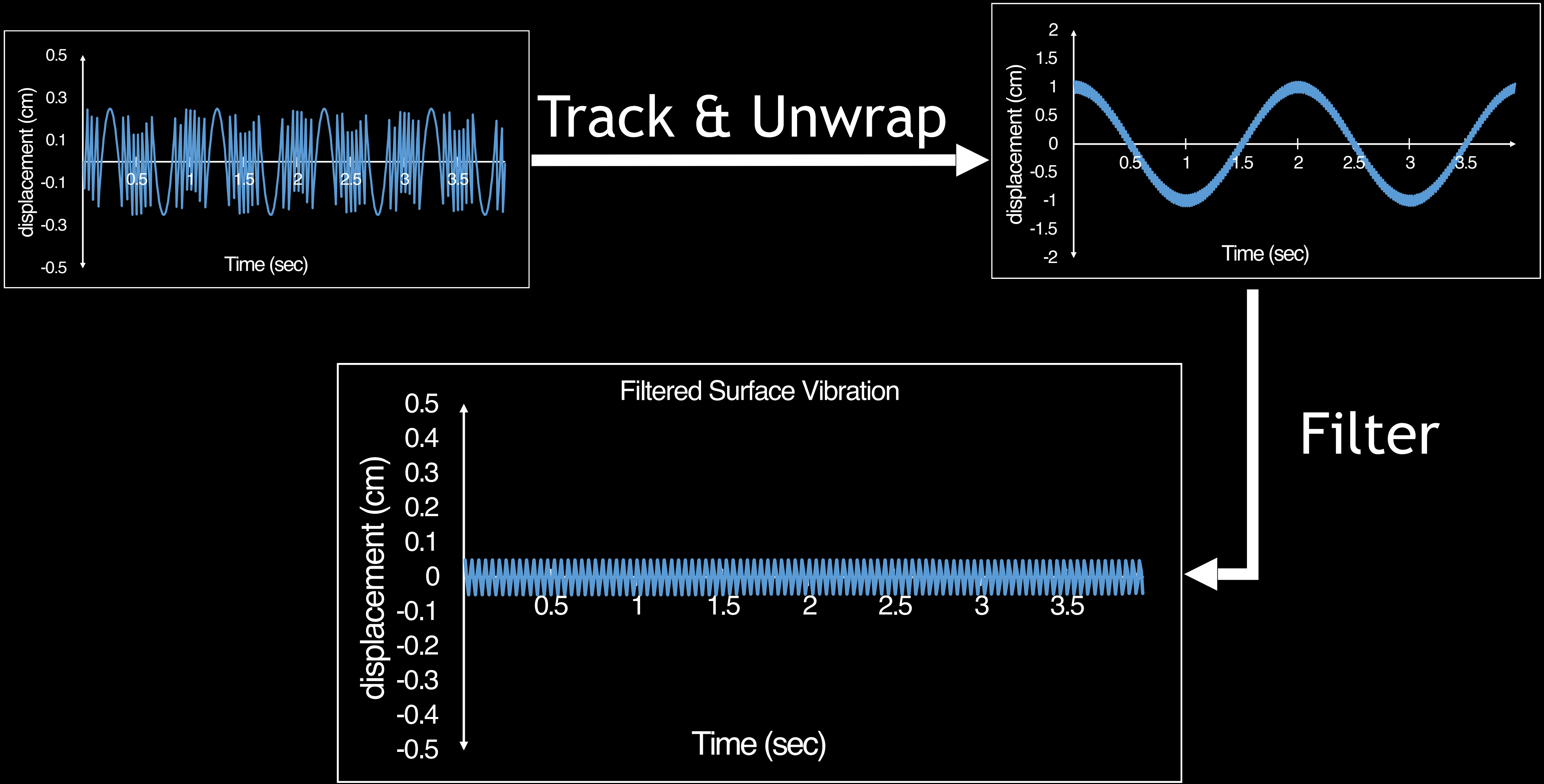
Dealing with Waves



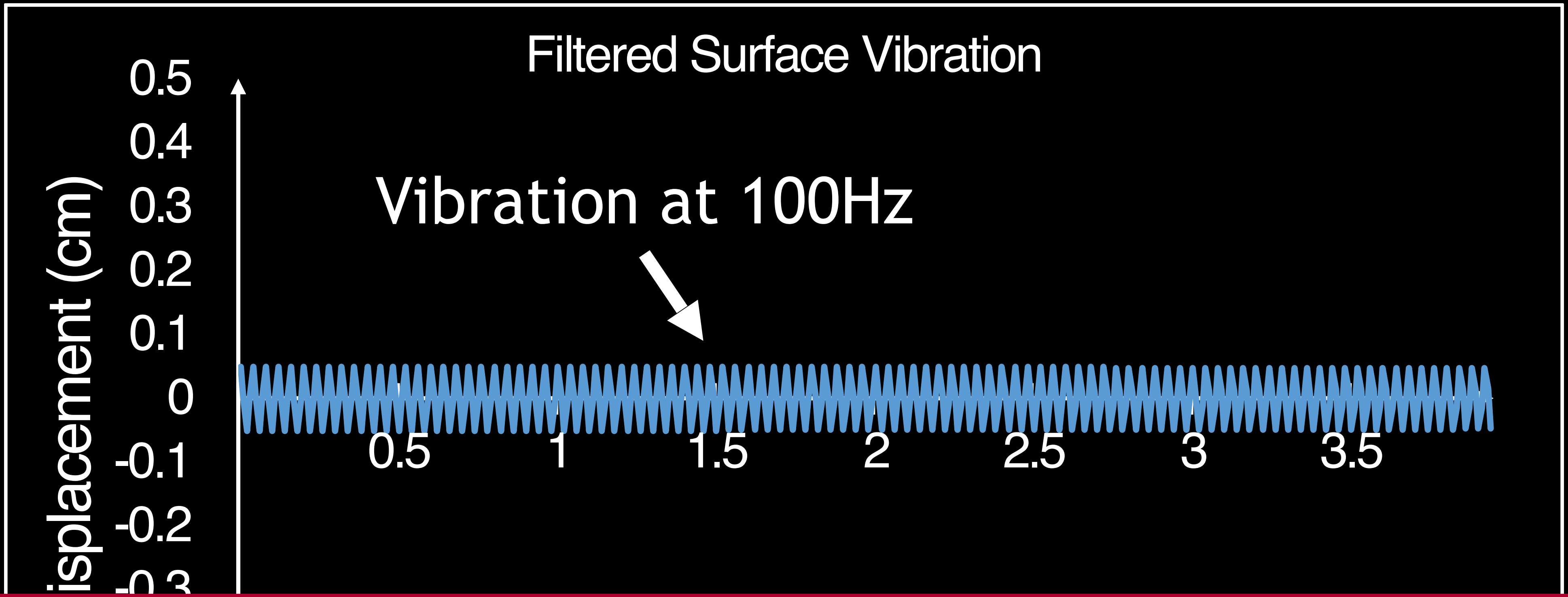
Dealing with Waves



Dealing with Waves

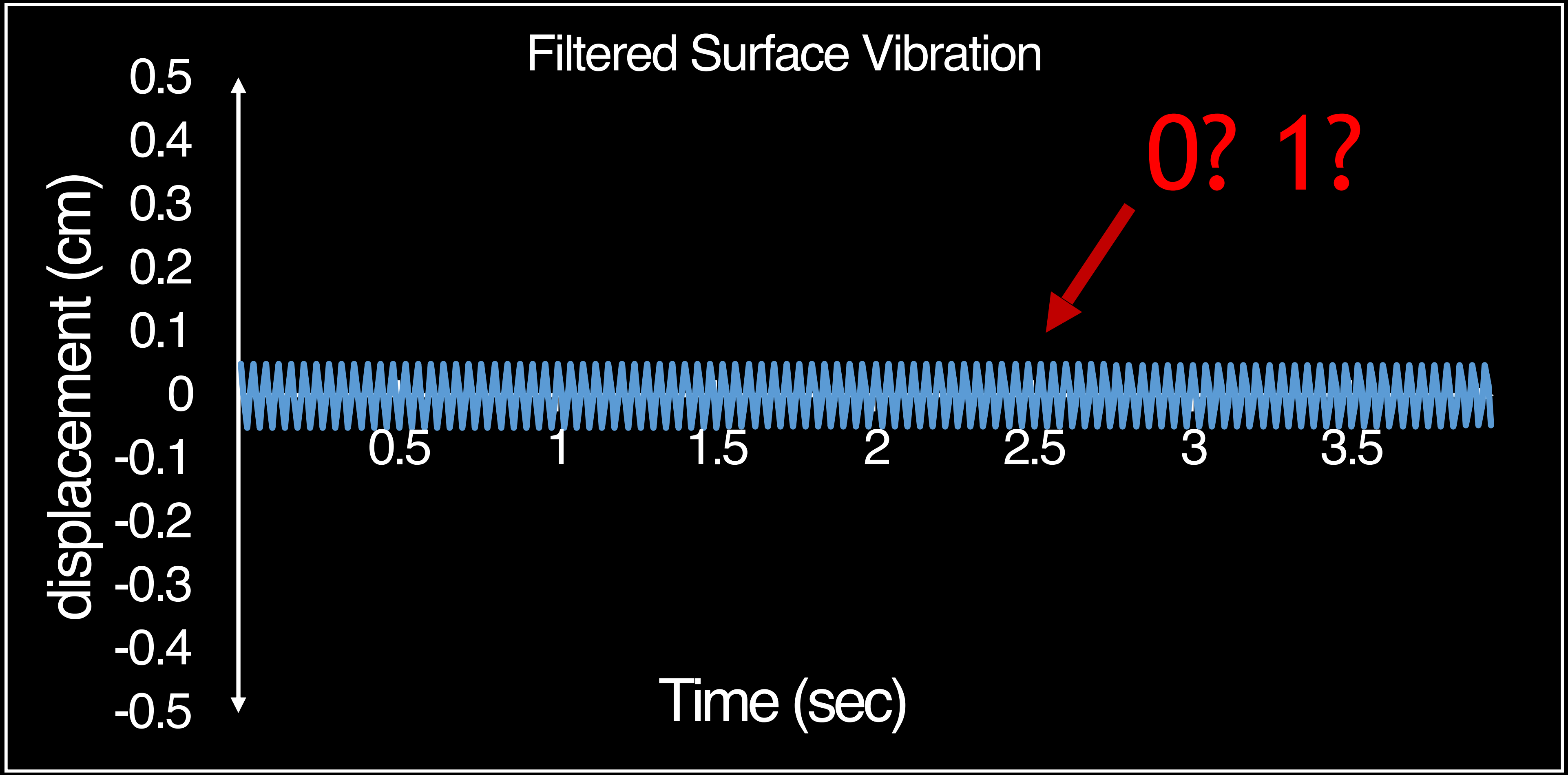


Dealing with Waves



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

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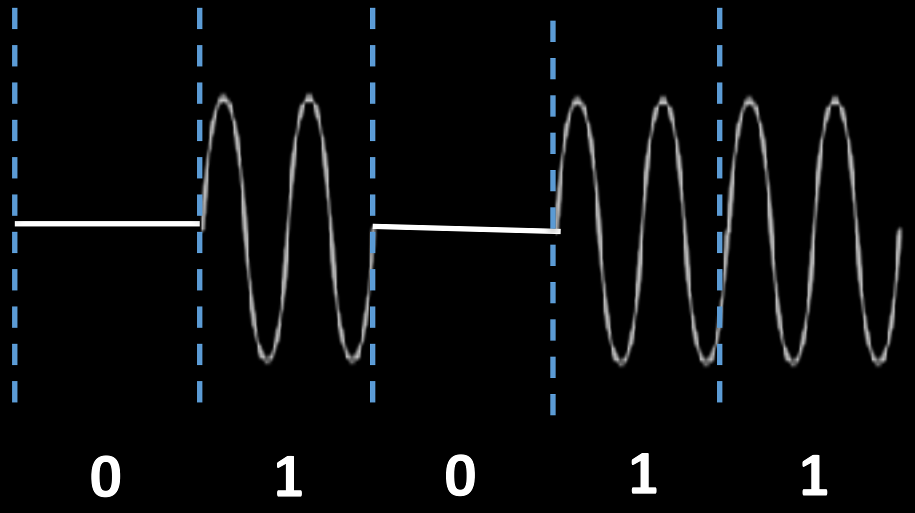
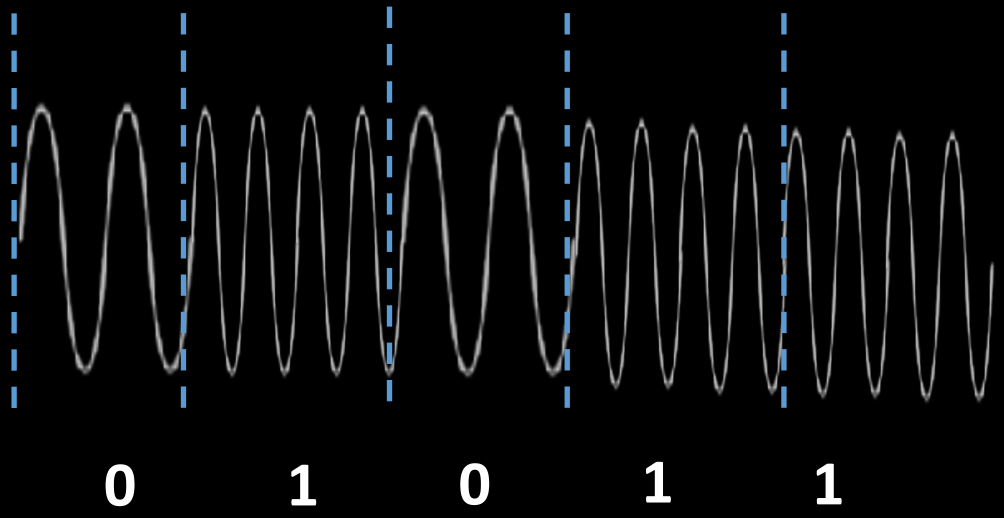
ON-OFF keying, FM0/Manchester, FSK

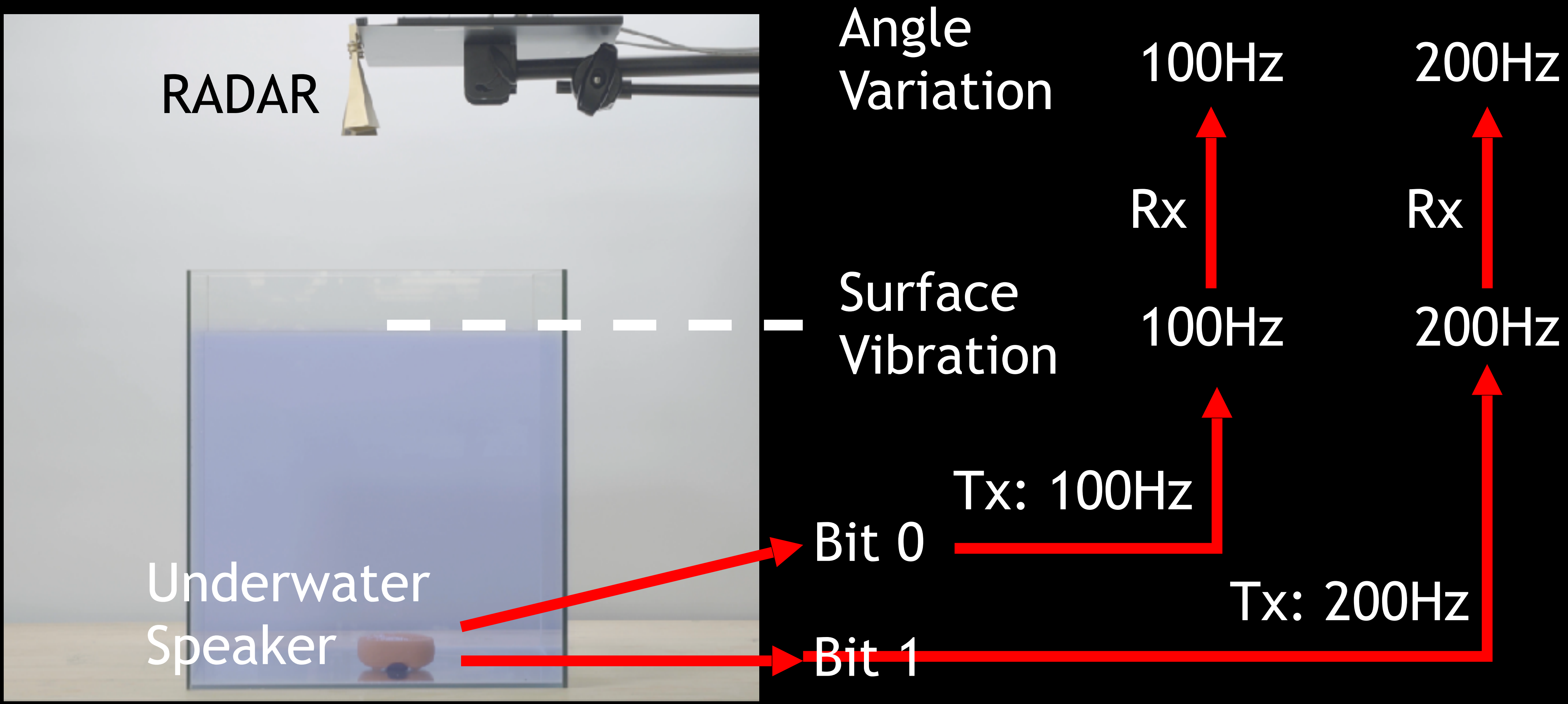


On – Off Keying



Frequency shift keying (FSK)

Decoding Information



Standard Modulation Schemes?

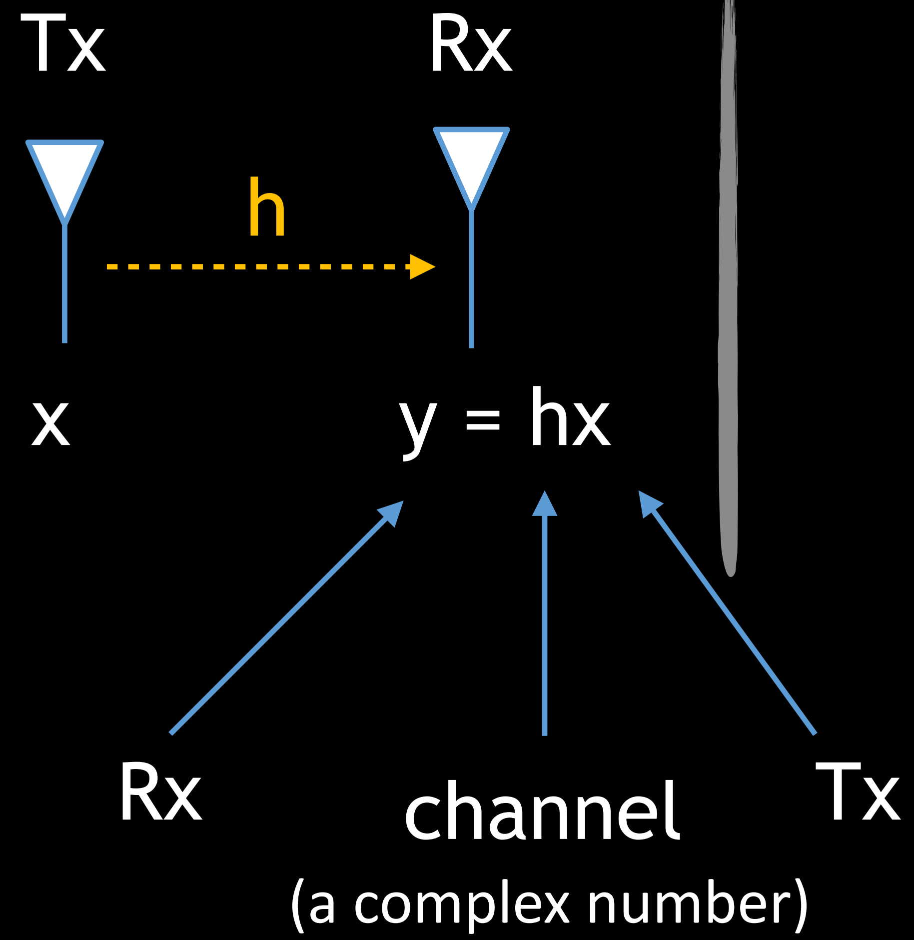
The wireless channel

- Mathematics & Physical Interpretation
- Upconversion & Downconversion

Modulation & Demodulation

The Wireless Channel (Math)

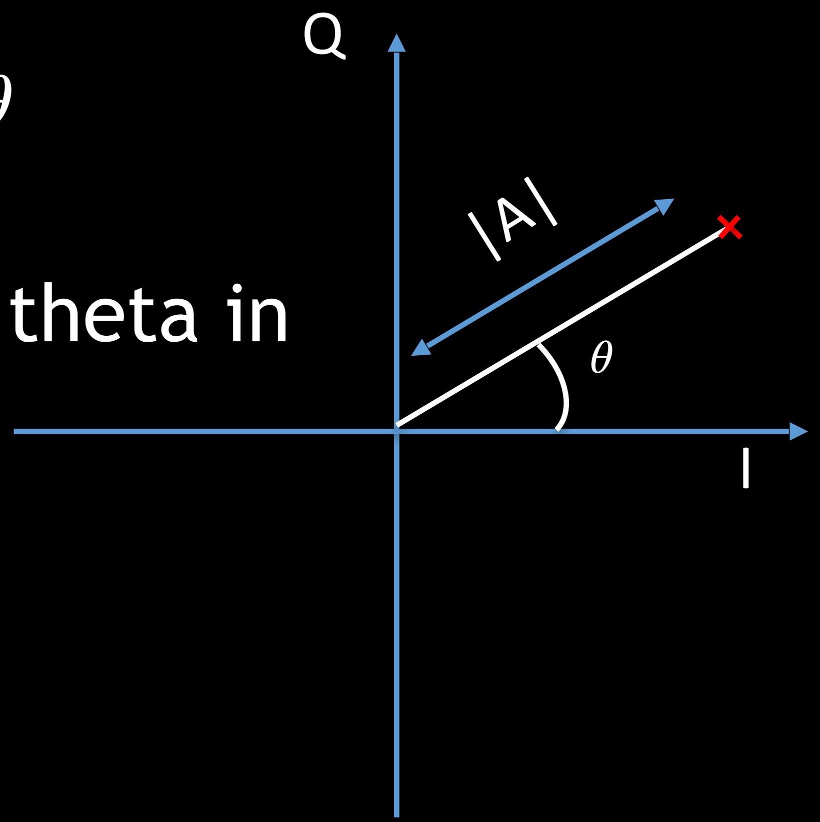
Complex number, I/Q plane, example



E.g., h = 1/4 + i*(1/4)

$$h = Ae^{j\theta}$$

what are A and theta in this example?



Encoding & Decoding

Symbols (+/-1) Example, Preambles, Channel Estimation, Length of Preamble

1. Bits -> Symbols

$$Bits = \{1,0\}$$

$$Symbols = \{-1, +1\}$$

2. Example channel: x->y

$$h = \frac{1}{4} + \frac{1}{4}j$$

3. Recovered symbols

x'=y/h

4. Decoded bits

Bits	0	1	1	0	0
Symbols = X	-1	+1	+1	-1	+1
Y = hX	-1/4-1/4j	1/4+1/4j	1/4+1/4j	-1/4-1/4j	1/4+1/4j
Decoded Symbols = X’	-1	+1	+1	-1	+1
Decoded bits	0	1	1	0	0

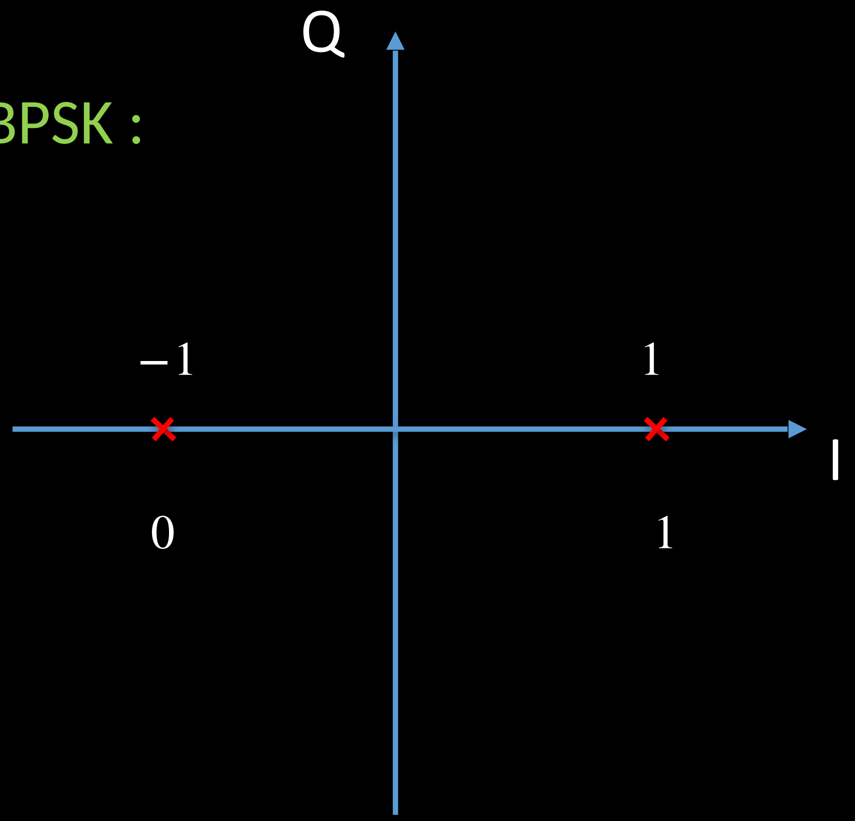
How can I estimate the channel?

Pros/Cons of long vs short preamble?

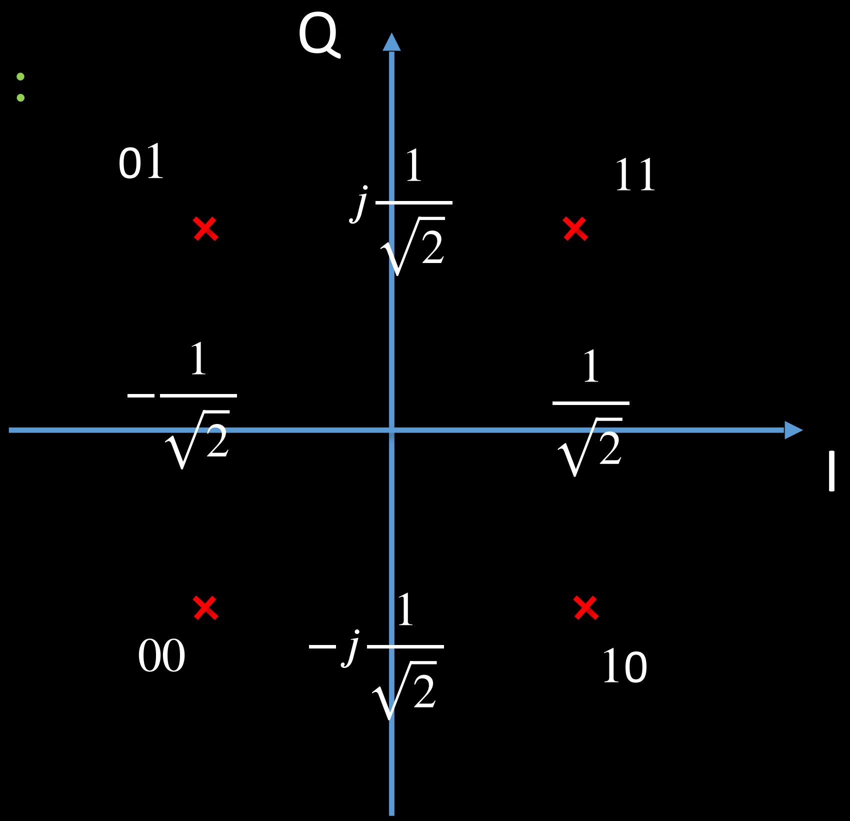
Modulation Schemes

Bits -> Complex number

BPSK :



QPSK :

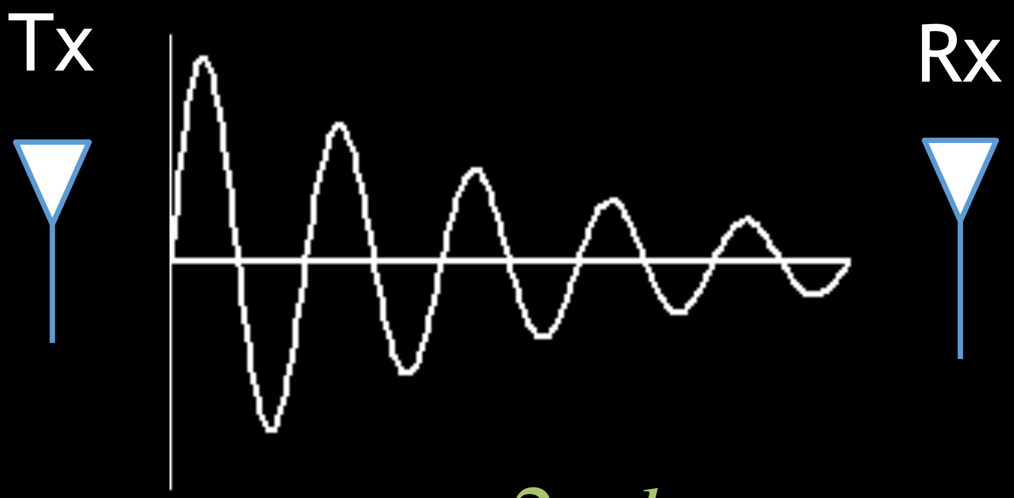


Pros/Cons of BPSK vs QPSK?

other modulation schemes?

The Wireless Channel (Physics)

Cosine (at frequency), 1 path, what happens over the medium (and why), why not baseband



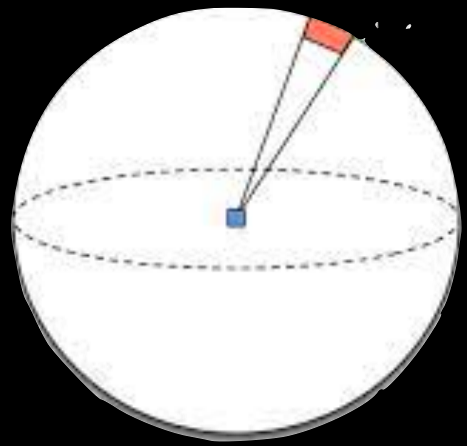
- Transmit a cosine (at frequency)
  why can't transmit without cosine?

- What is the channel?

$$h = Ae^{j\theta}$$

$$|A| = \frac{1}{d}$$

$$\theta = \frac{2\pi d}{\lambda}$$



$$x = \cos(2\pi f t)$$

$$y = \frac{1}{d}\cos(2\pi f(t-\tau))$$

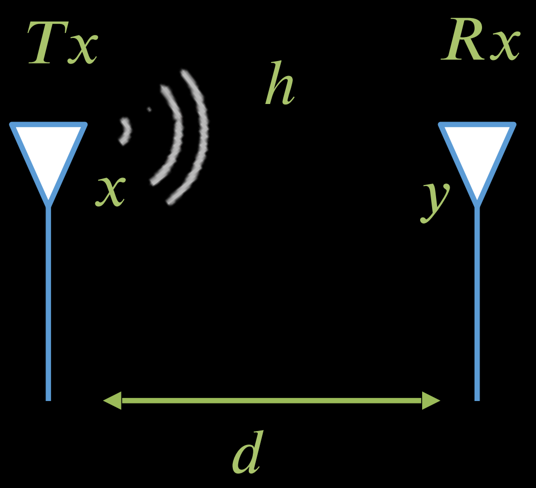
$$h = \frac{1}{d}e^{j\frac{2\pi d}{\lambda}}$$

Upconversion/Downconversion

How do we recover upon receiving?

Upconversion/Downconversion

How do we recover upon receiving?



$x = \mathrm{d}\,.\cos(2\pi f t)$ → d = Data (bits)

$\mathrm{y} = h\,.\,x$ → $\mathrm{y} = \mathrm{h}\,.\,\mathrm{d}\,.\cos(2\pi f t)$

$\mathrm{yd} = y * \cos(2\pi f t)$

$\mathrm{yd} = \mathrm{h}\,.\,\mathrm{d}\,.\cos(0) + \mathrm{h}\,.\,\mathrm{d}\,.\cos\left(4\pi f t\right)$ → yd = Downconverted y

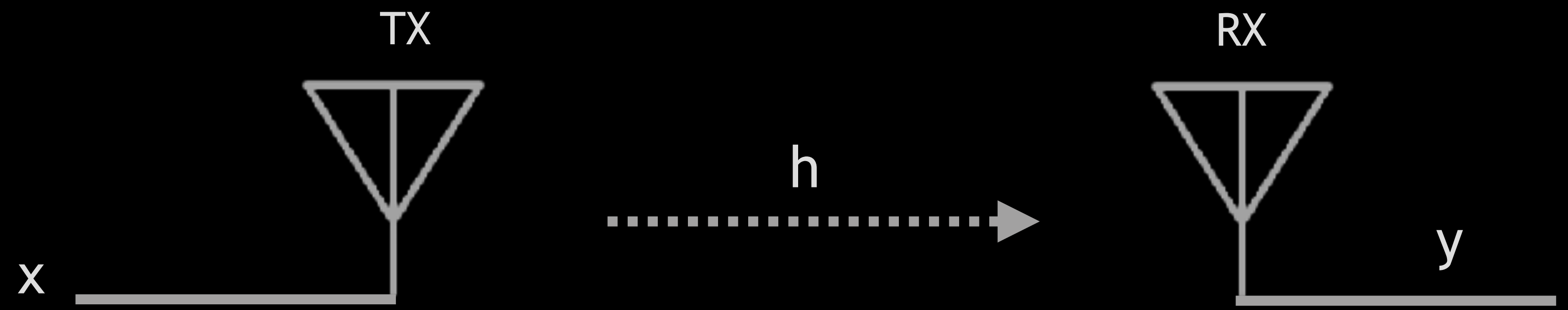
$\mathrm{LPF}\{\,\mathrm{yd}\} = \mathrm{h}\,.\,\mathrm{d}$ → LPF = low pass filter, you can obtain data now by normalizing by the channel h

MIMO/Beamforming

- Power from Tx->Rx
- Multi-antenna transmissions
- Transmit beamforming / pre-coding
- Receive beamforming
- MIMO

Single Tx-Rx

x/y, P_Tx, P_Rx, SNR



y = hx+n

$$P_{tx} = |x|^2 = 1$$

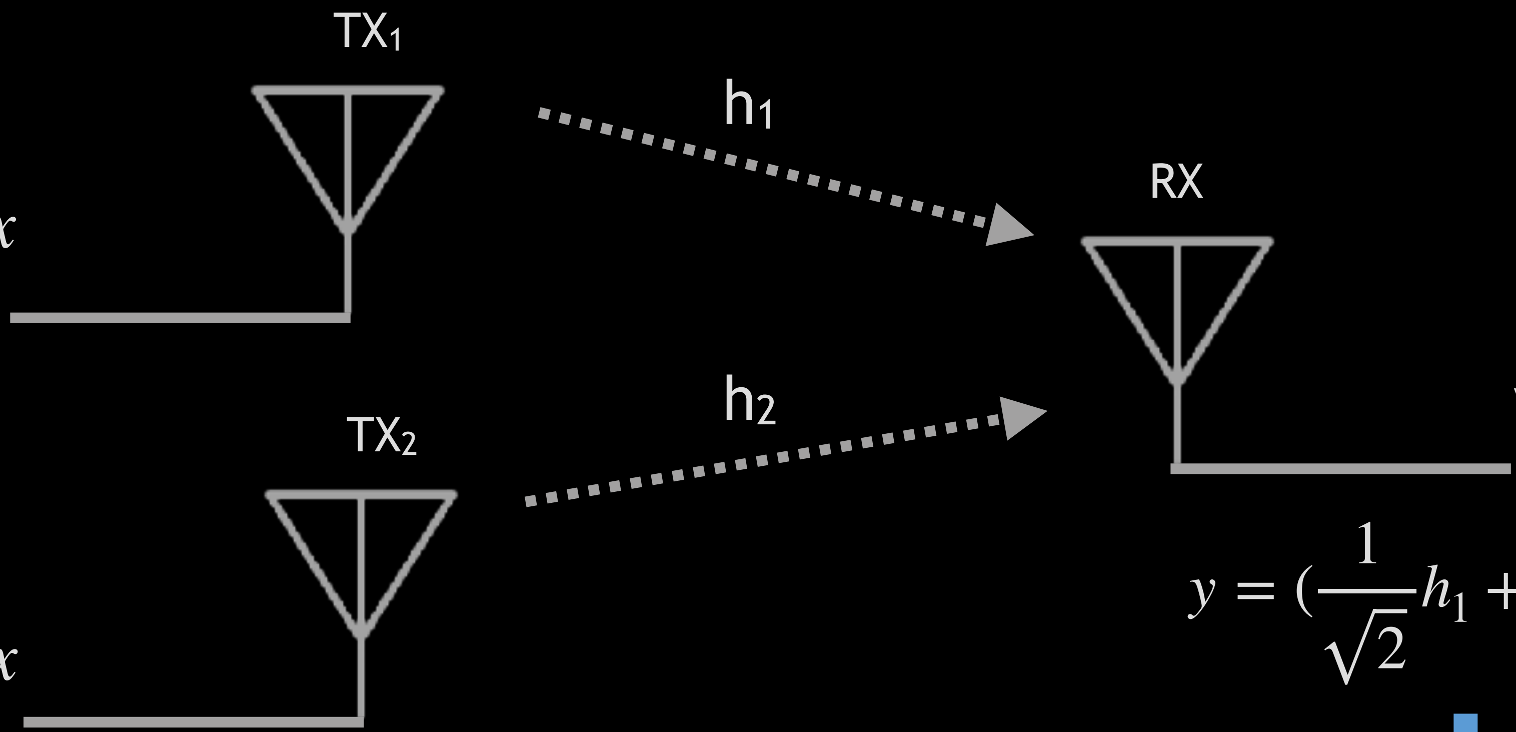
$$P_{rx} = |hx|^2 = P_{tx}|h|^2$$

$$\text{SNR} = \frac{P_{tx}|h|^2}{|n|^2} \approx \frac{|h|^2}{|n|^2}$$

Same power, divided across 2 ants

Assume same channel, P_Rx=?, why?

$$x_1 = \frac{1}{\sqrt{2}}x$$



$$x_2 = \frac{1}{\sqrt{2}}x$$

y = $h_1x_1+h_2x_2+n$

$$y = (\frac{1}{\sqrt{2}}h_1 + \frac{1}{\sqrt{2}}h_2)x$$

$$h_1 = h_2 = h$$

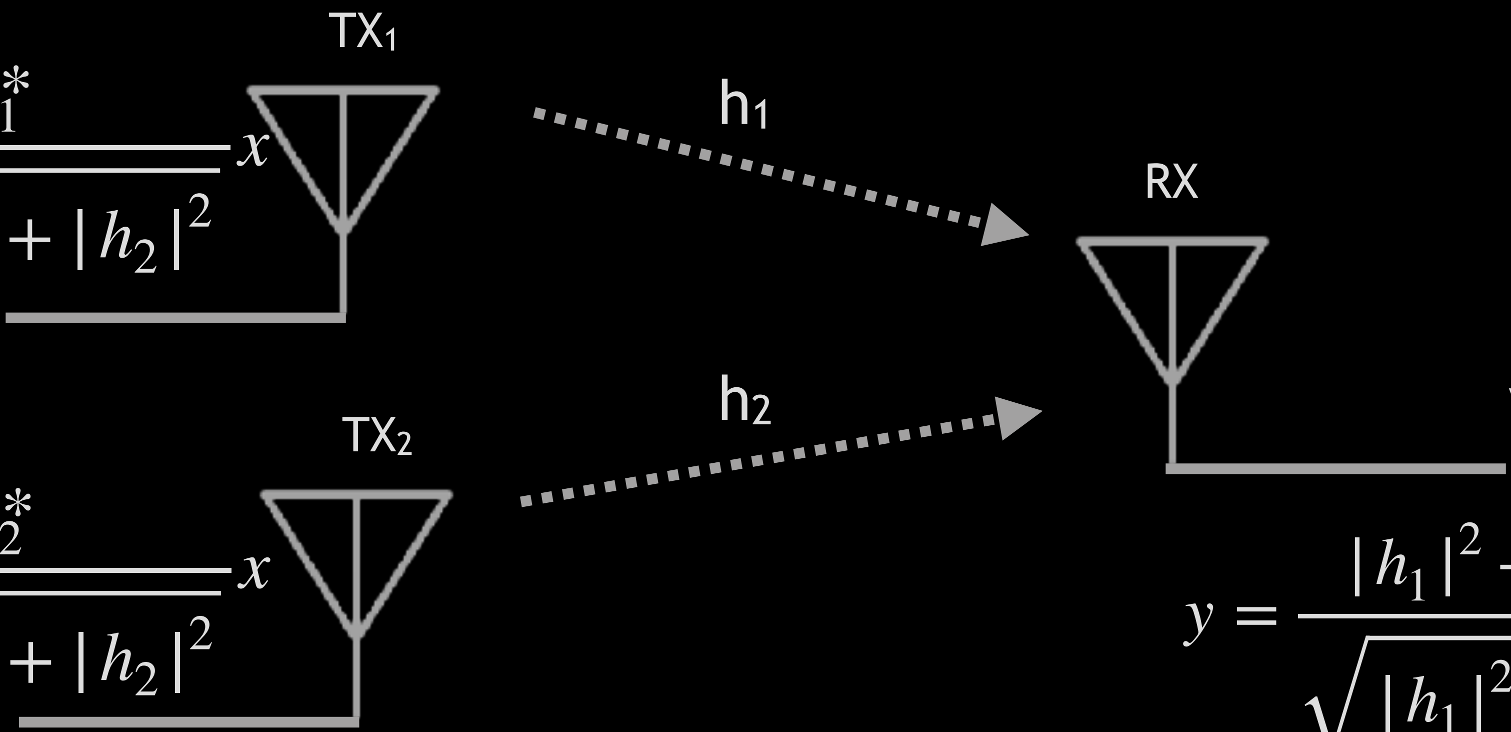
$$y = \sqrt{2}hx$$

$$P_{rx} = 2|h|^2 P_{tx}$$

$$P_{total} = P_1 + P_2 = P_{tx}$$

More realistic channels: how to precode?

Assume h1 different h2, where to Tx more power?



$$x_1 = \frac{h_1^*}{\sqrt{|h_1|^2 + |h_2|^2}} x$$

$$x_2 = \frac{h_2^*}{\sqrt{|h_1|^2 + |h_2|^2}} x$$

$y = h_1 x_1 + h_2 x_2 + n$

$$y = \frac{|h_1|^2 + |h_2|^2}{\sqrt{|h_1|^2 + |h_2|^2}} x + n$$

$$y = \sqrt{|h_1|^2 + |h_2|^2}\, x + n$$

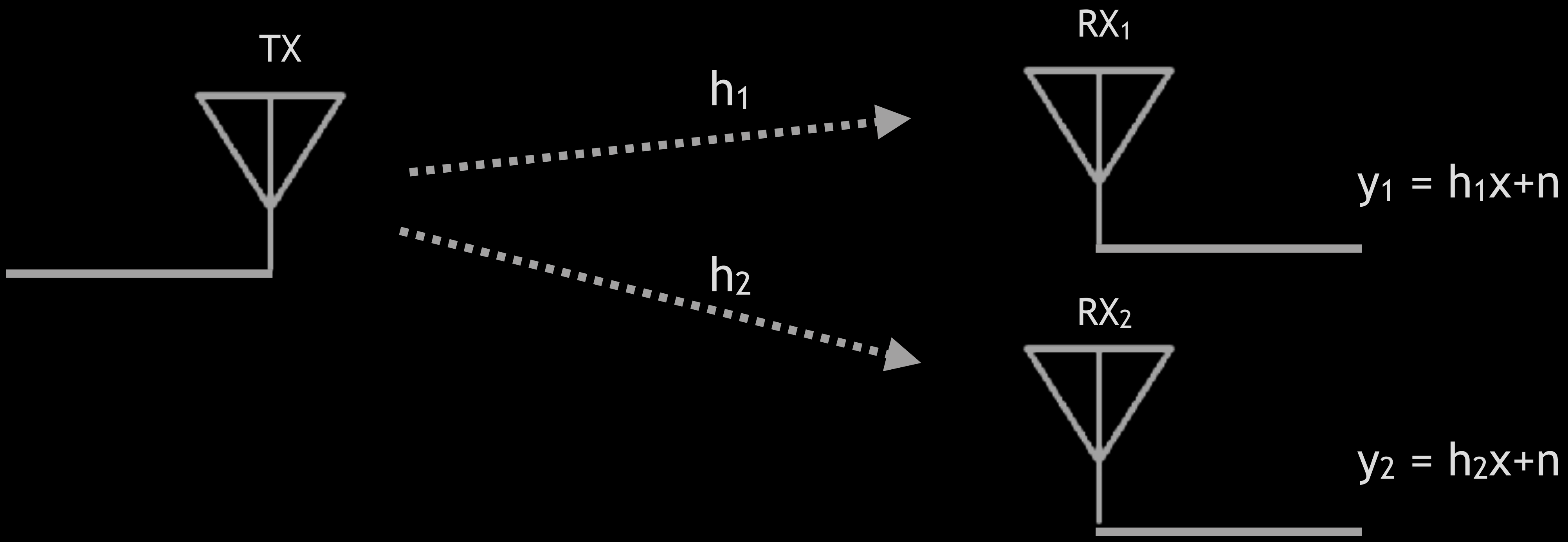
$$P_{total} = P_1 + P_2 = P_{tx}$$

Maximal Ratio Combining

$$P_{rx} = (|h_1|^2 + |h_2|^2) P_{tx}$$

Rx multi-antenna diversity

Two Rx's, how to combine?

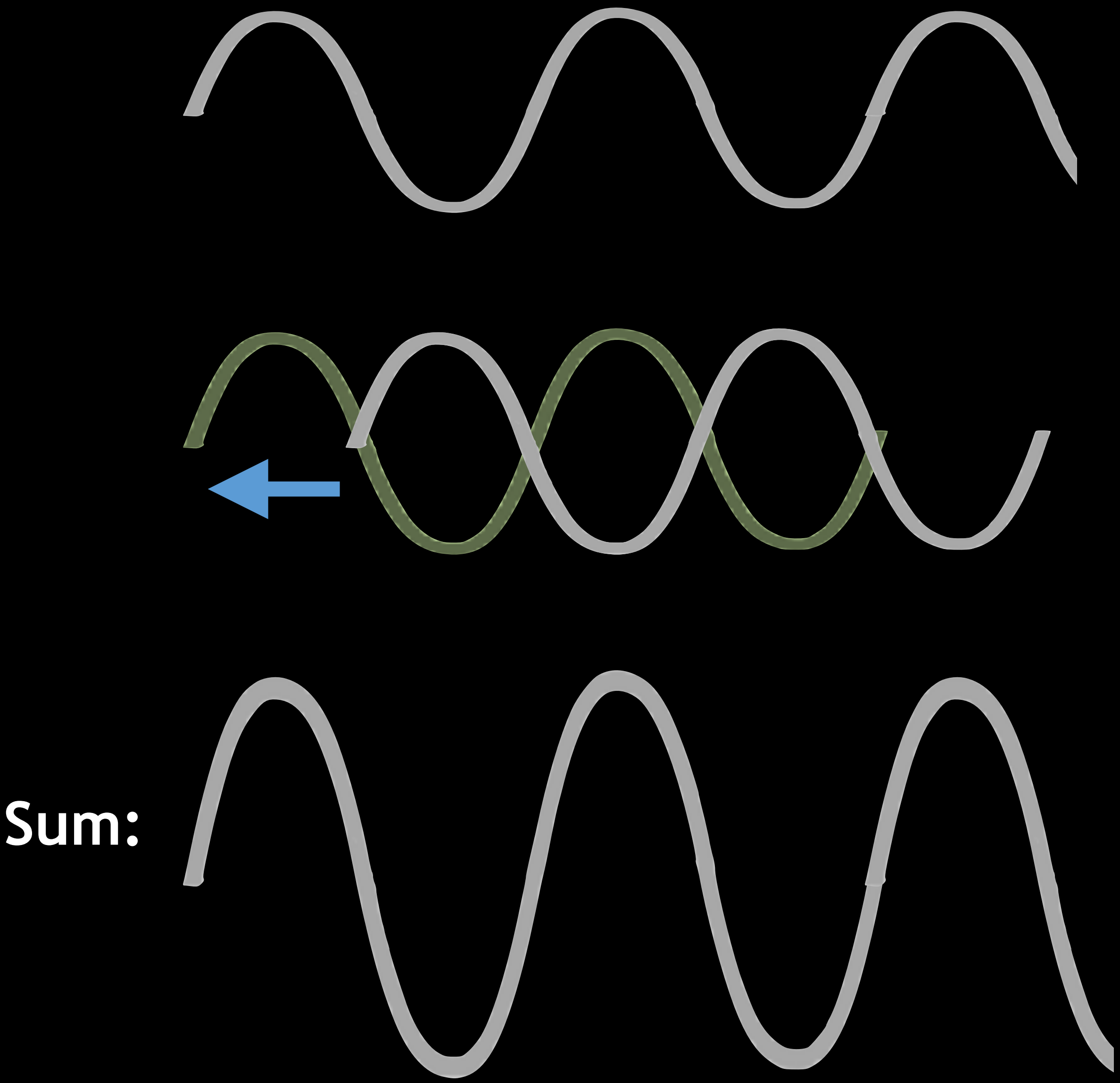


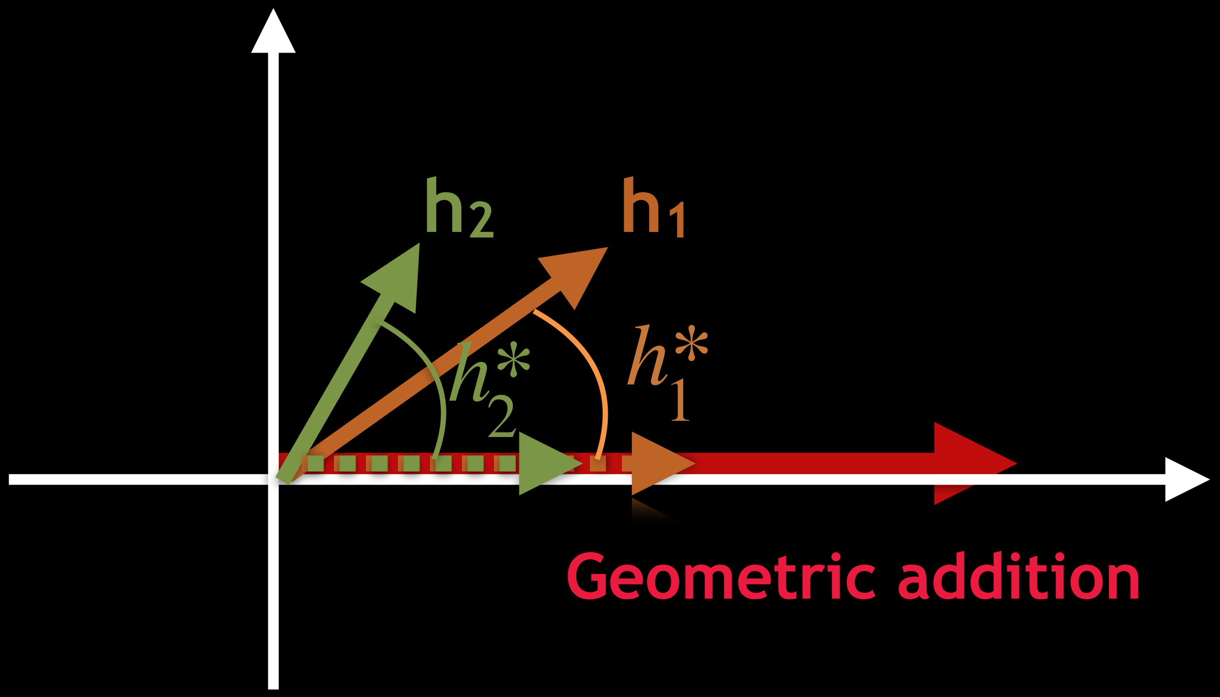
$$y = \frac{h_1^* y_1 + h_2^* y_2}{\sqrt{|h_1|^2 + |h_2|^2}} = \frac{h_1^*(h_1 x + n) + h_2^*(h_2 x + n)}{\sqrt{|h_1|^2 + |h_2|^2}} = \frac{(|h_1|^2 + |h_2|^2)x + (h_1^* + h_2^*)n}{\sqrt{|h_1|^2 + |h_2|^2}}$$

$$P_{rx} = (|h_1|^2 + |h_2|^2)P_{tx}$$

Interpretation of pre-coding

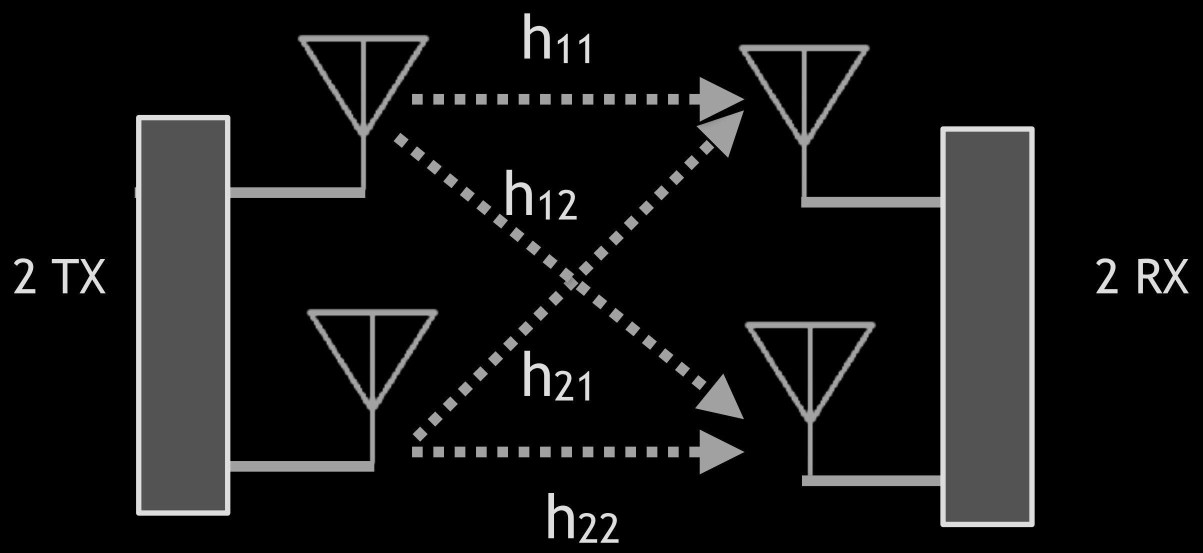
a) shifting in time, b) on the I-Q plane





Extension to MIMO

high-level diagram, diversity gain



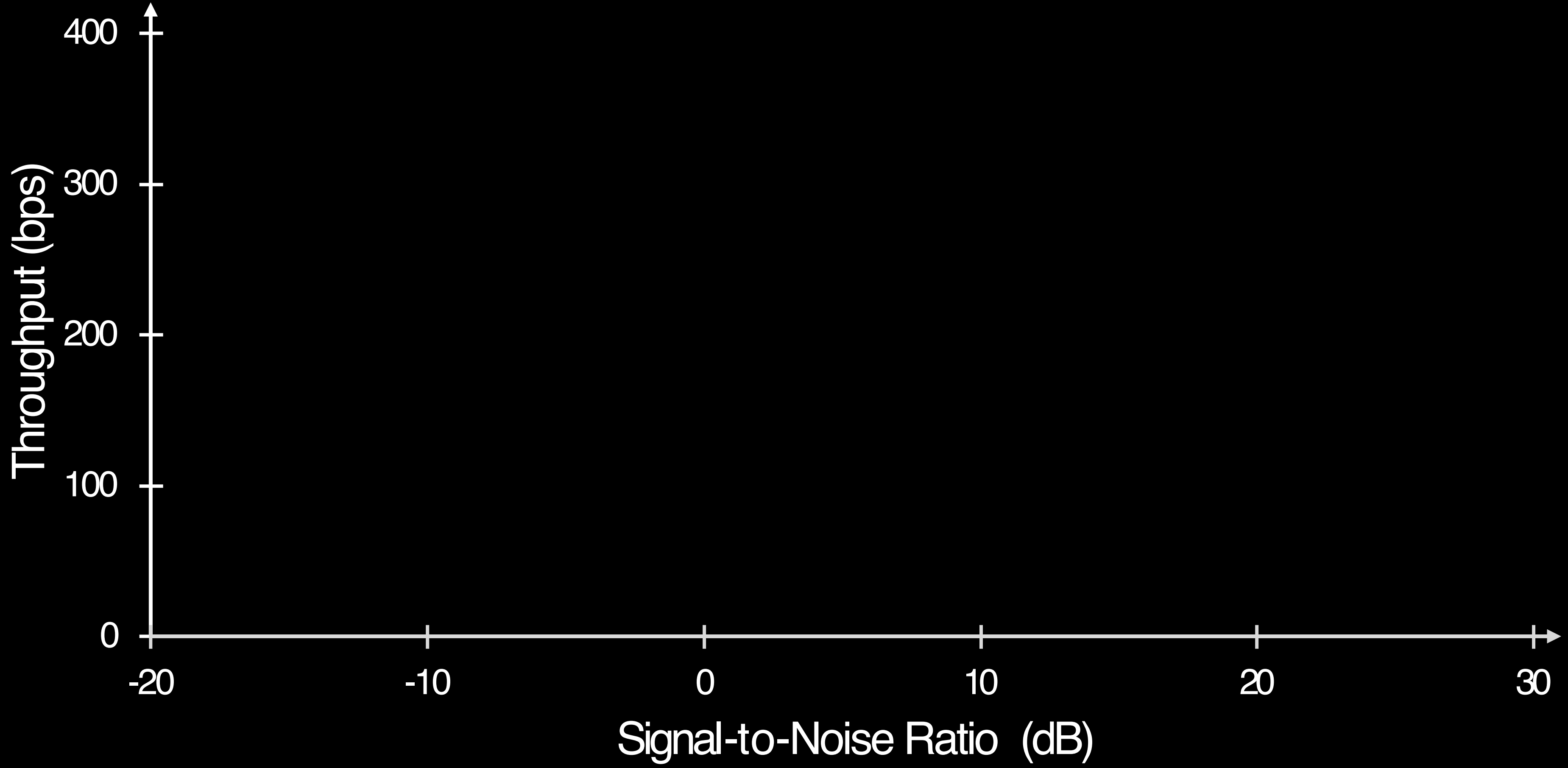
Gain for Diversity

$$G = W \log(1 + SNR)$$

Let’s go back to TARF

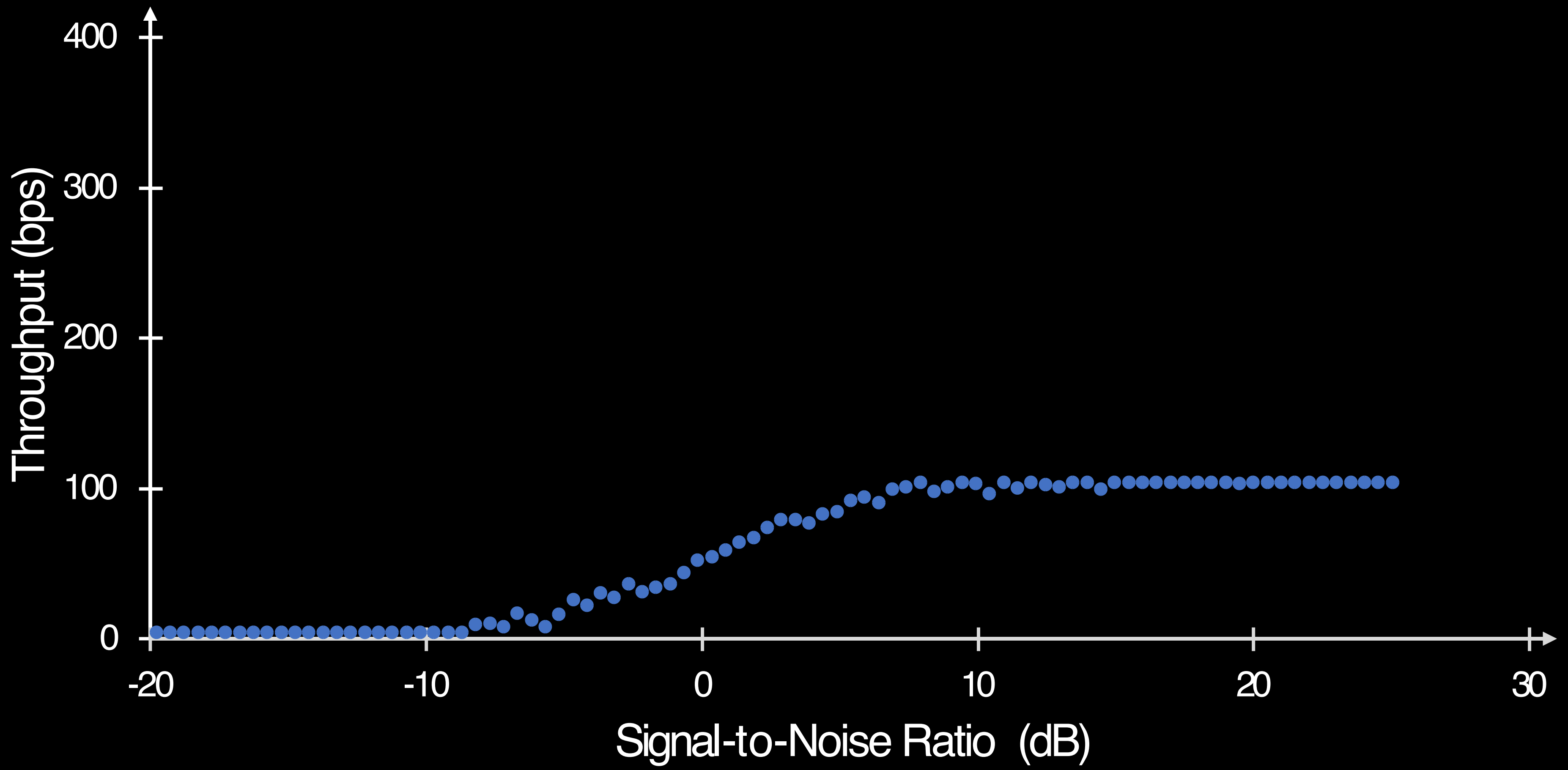
Throughput Results

Experiment: Vary the Power and Depth of Underwater Transmission



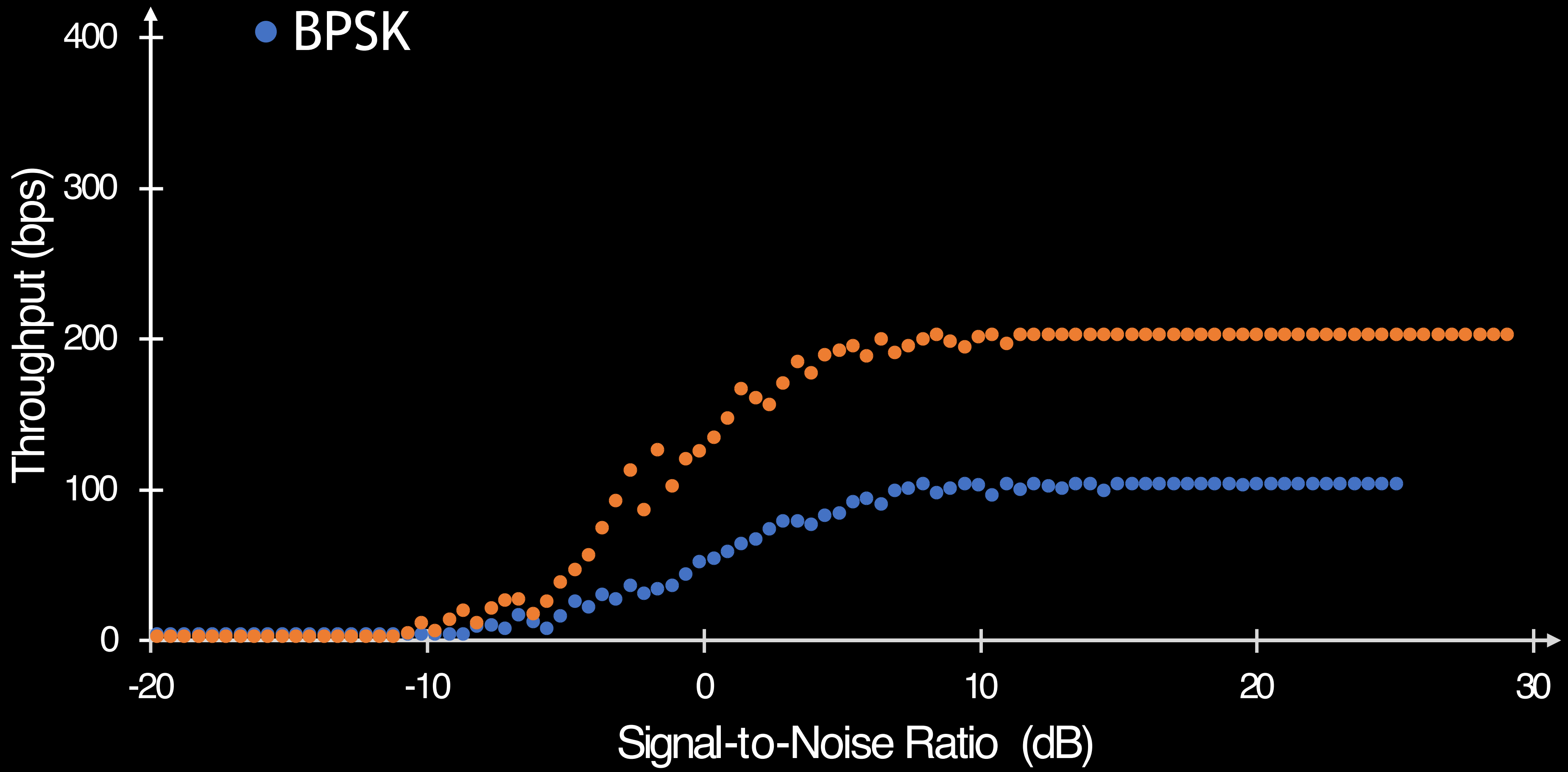
Throughput Results

Experiment: Vary the Power and Depth of Underwater Transmission



Throughput Results

Experiment: Vary the Power and Depth of Underwater Transmission



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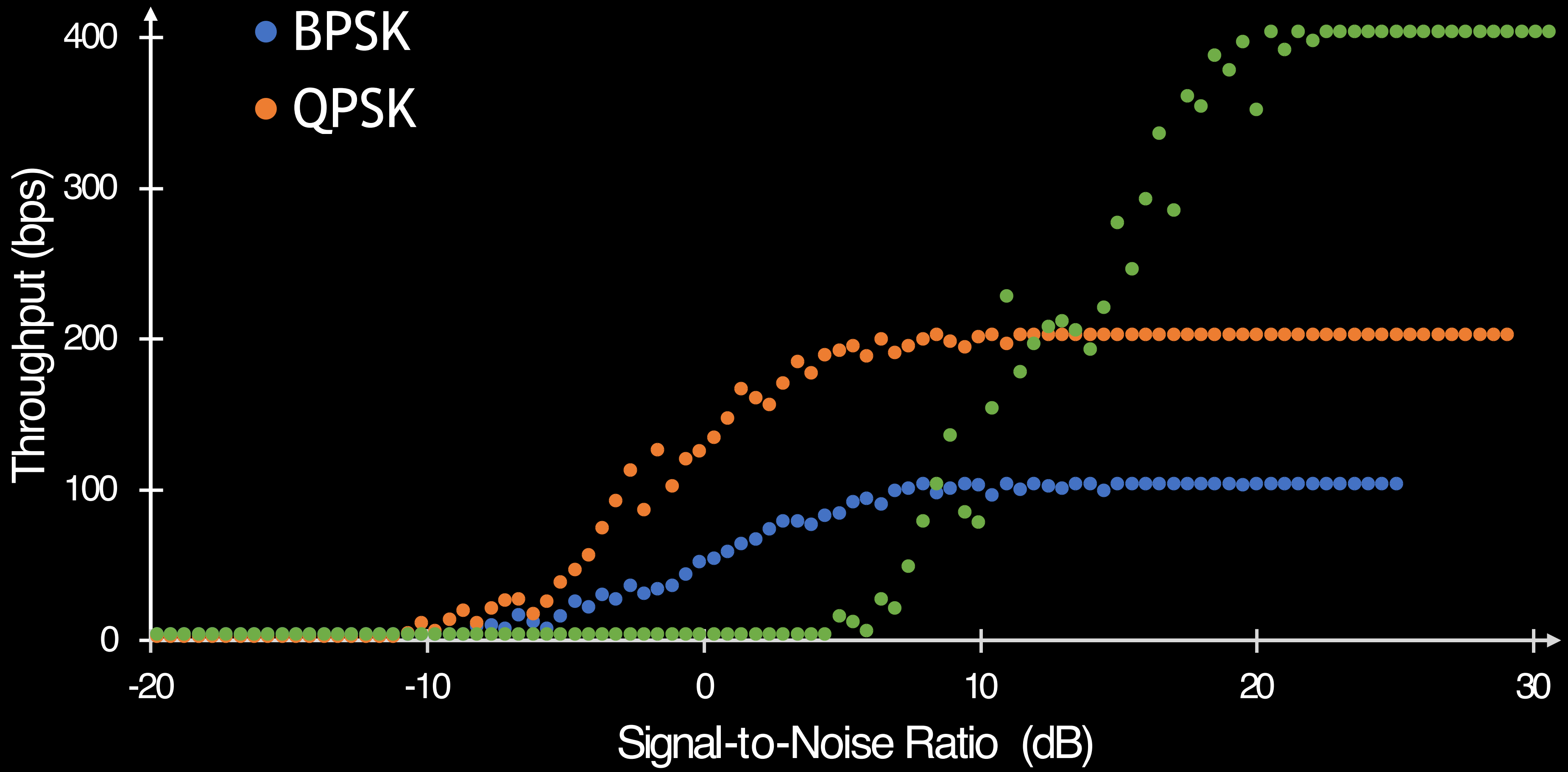
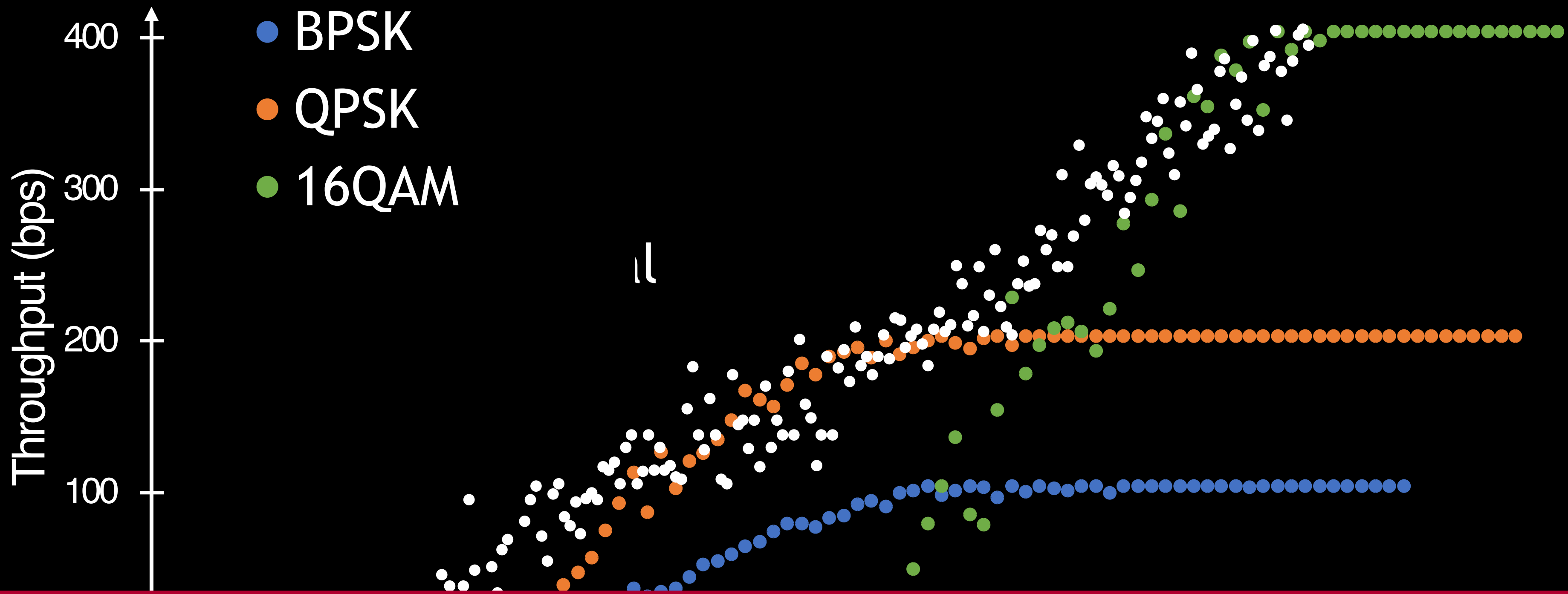


Throughput Results

Experiment: Vary the Power and Depth of Underwater Transmission



TARF is a valid communication technology and can adapt to different channels

Objectives of Today's Lecture

Learn the **fundamentals** of communications and emerging technologies for underwater-to-air comms

1. What are the fundamentals of end-to-end wireless communications?
   - The physical, mathematical, engineering, and design fundamentals
   - Why are these systems designed the way they are

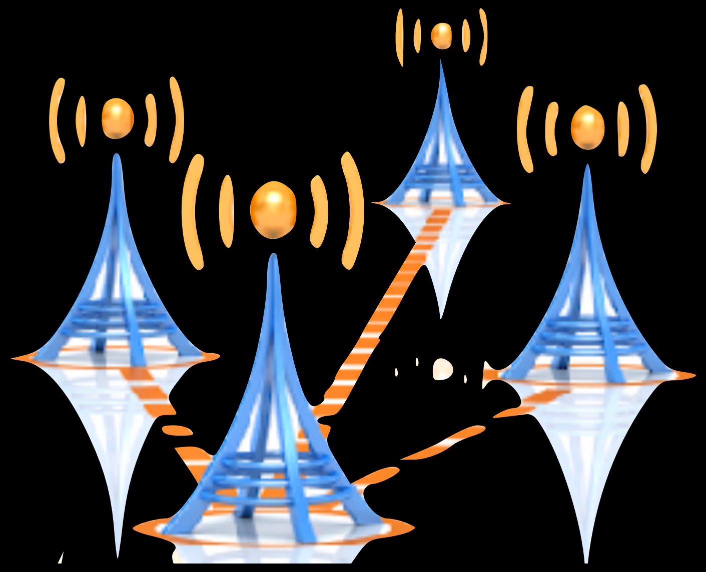
2. How can we use wireless sensing *for* communications? (converse of last 2 lectures)

3. How do underwater-to-air communication systems work?

This Class: Wireless Communications

1) Required

- The Wireless Channel (Chapter) - summary required
- Underwater-to-Air Communications - review required



2) Optional

- 802.11n+: Random Access Heterogeneous MIMO Networks
- ZigZag Decoding: Combating Hidden Terminals in Wireless Networks
- Full-Duplex Practical, Real-time, Full Duplex Wireless

Next Class: Battery-Free Computing & Communication

Prep a 1-min pitch for your project idea

1) Required (Reviews)

- WISP: Design of an RFID-Based Battery-Free Programmable Sensing Platform
- Minding the billions: Ultra-wideband localization for deployed rfid tags

2) Optional Readings

- Ambient backscatter: Wireless communication out of thin air
- Wi-Fi Backscatter: Internet Connectivity for RF-Powered Devices
- Battery-Free Game Boy