http://www.mit.edu/~fadel/courses/MAS.wireless

MAS.S61

Wireless & Mobile Sensing

Lecture 4:
Fundamentals of Wireless Communications

Lecturer
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Verizon launches 6G Initiative, promising to transform wireless communication

News By Nandika Ravi published September 23, 2025

From faster speeds, to being able to "sense" the environment, and integrating AI.

Comments (0)

Furthermore, Nokia states that the new network will have the ability to "sense" the environment by using signals that will essentially bounce off obstacles or objects that come in its path. This will allow it to figure out what those objects are, where they are, how fast they're moving, and what they're made of.

By combining this information with AI, the network can create a "digital twin" of the physical world

September 18, 2025

Next G Alliance Releases Landmark Report on Integrated Sensing and Communication for 6G Innovation — Enabling a Paradigm Shift in Next-Generation Wireless Networks

ATIS' Next G Alliance (NGA), the leading North American authority on 6G, today announced the release of a landmark white paper on Integrated Sensing and Communication (ISAC), a transformative capability expected to define the 6G era. The report explores how ISAC will position 6G as a driver of innovation across industries such as smart homes, transportation, environmental monitoring, healthcare, manufacturing, and public safety.

SMART HOME REPORT TECH

Inside Philips Hue's plans to make all your lights motion sensors

Hue's CTO explains how its new MotionAware feature works, why it took so long, and why it's better than previous RF sensing efforts.

by Jennifer Pattison Tuohy

Sep 4, 2025, 8:30 AM EDT

28 Comments (All New)

Mobile & Wireless Sensing

sensing the physical world & transmitting data wirelessly

sensing via the wireless signals themselves

So far

Mobile & Wireless Sensing

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 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

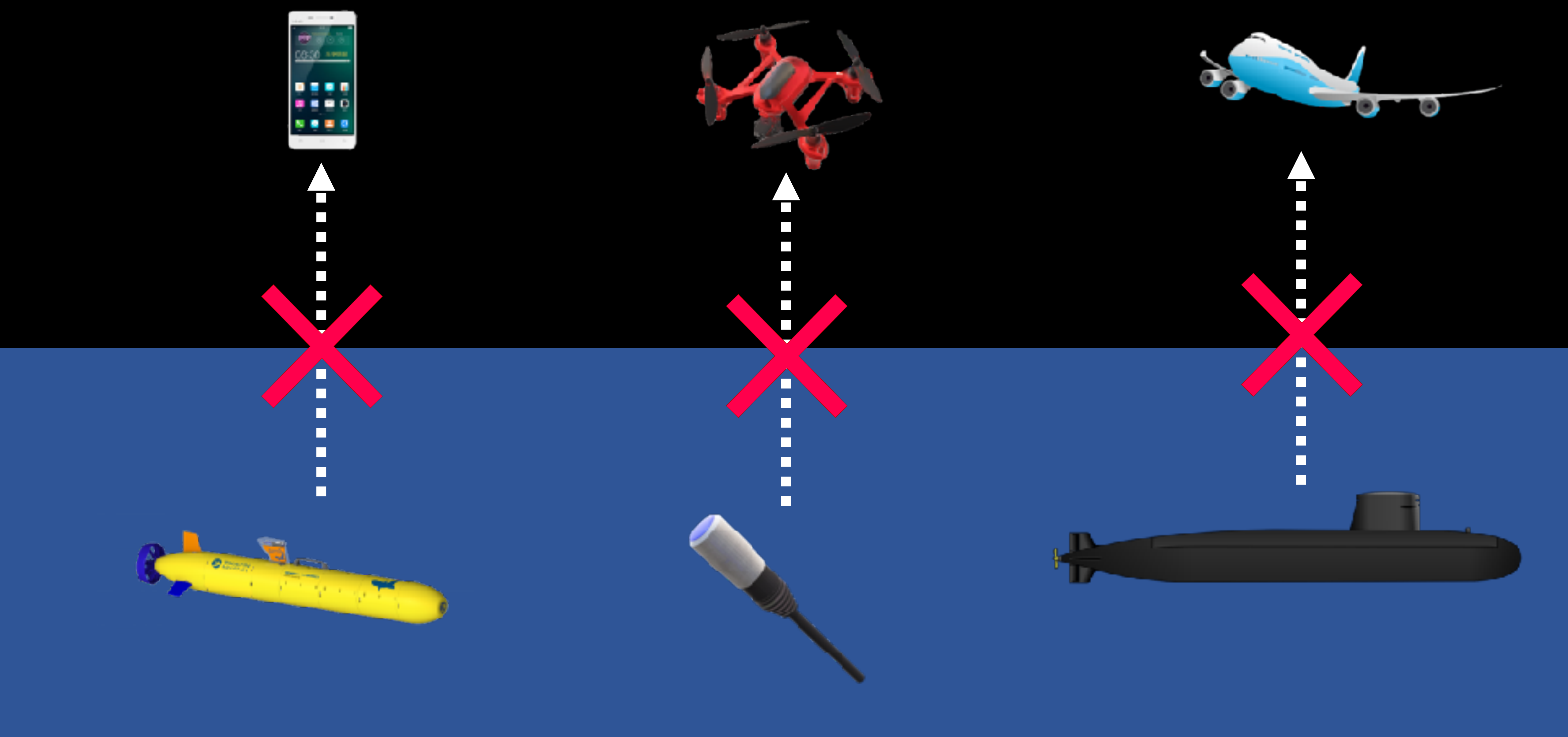
Finding Missing Airplanes

Ocean Scientific Exploration

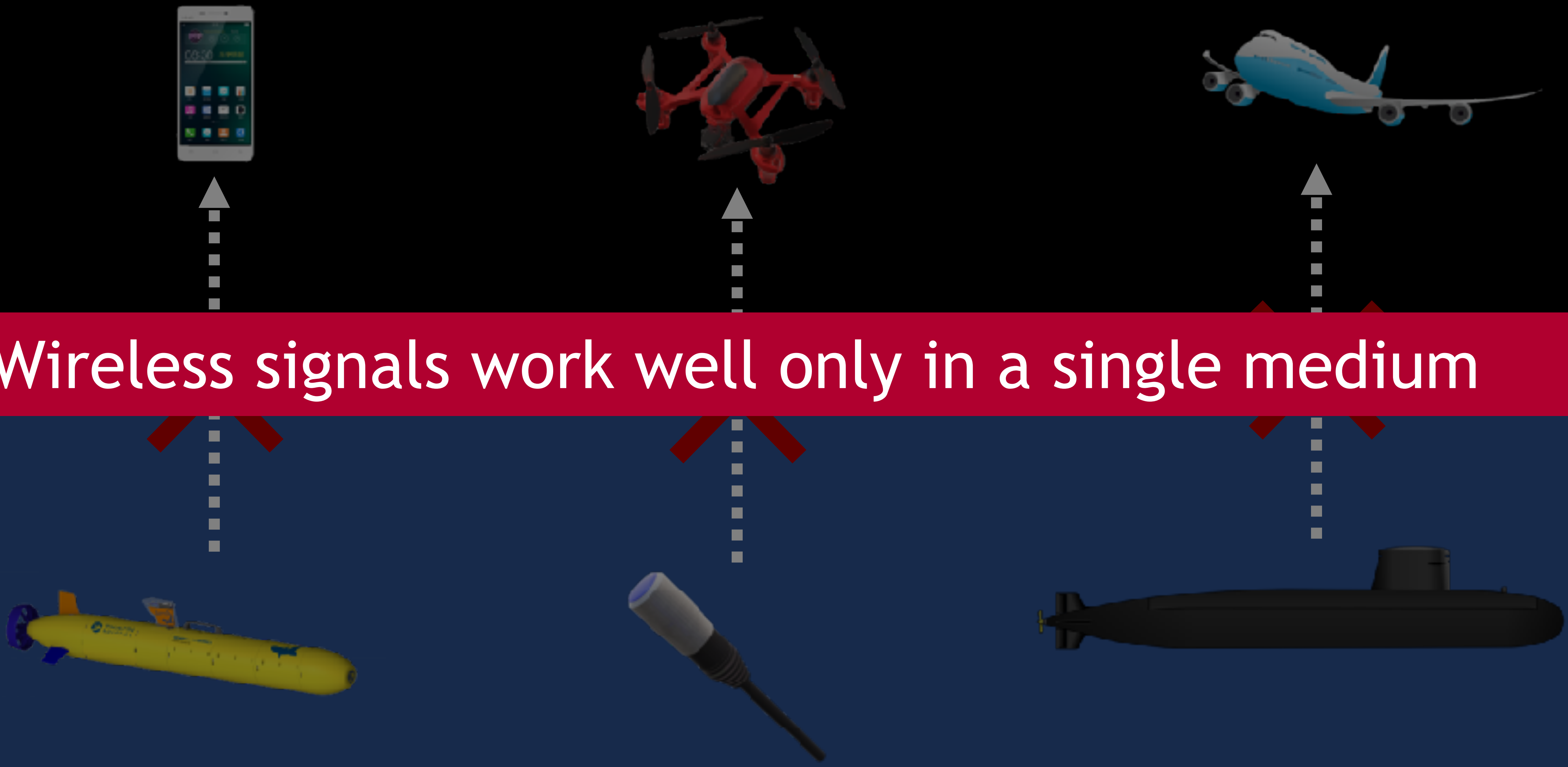
Underwater-to-Air Comm Applications

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

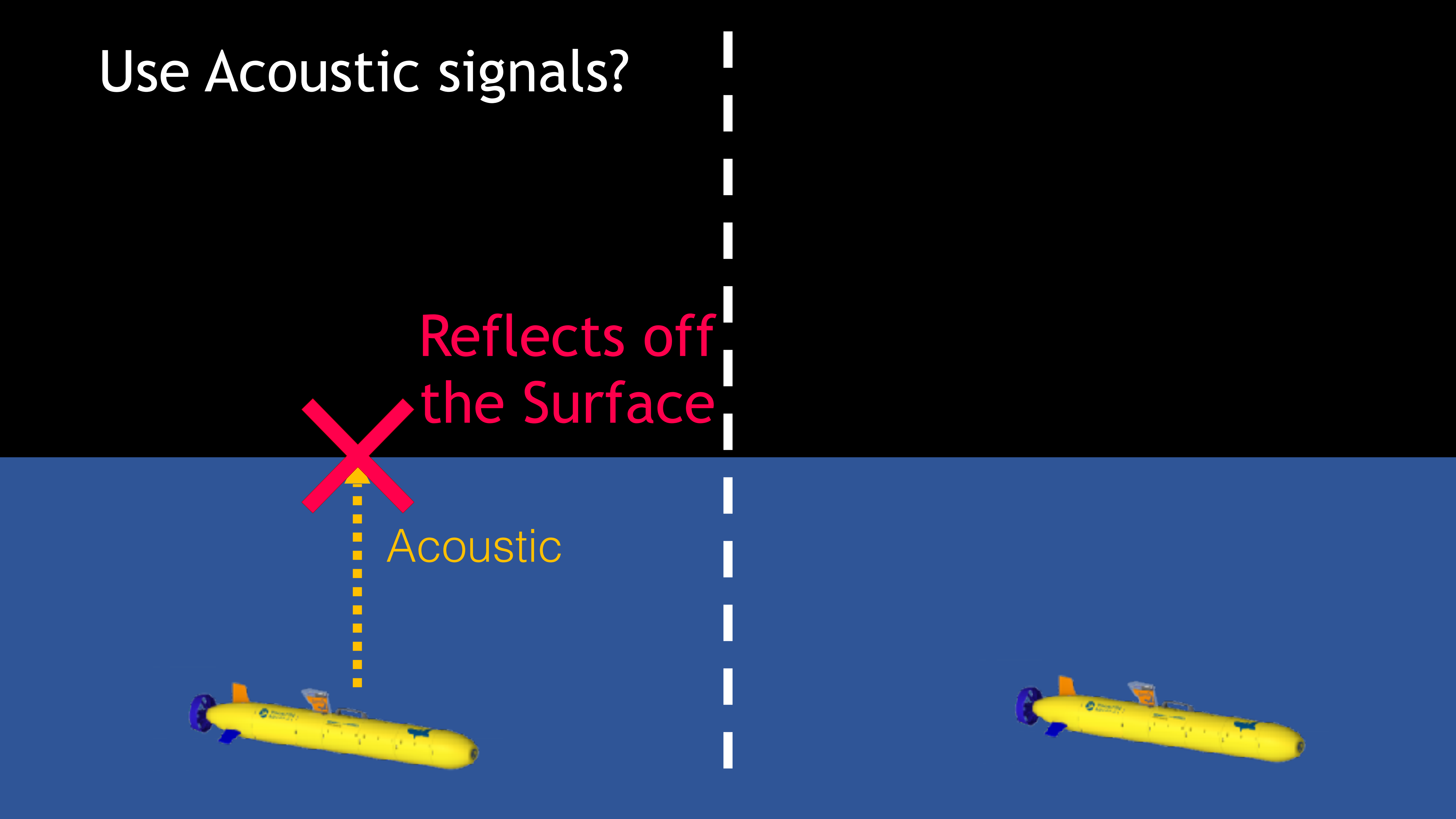
Wireless Signals Work Well Only in a Single Medium

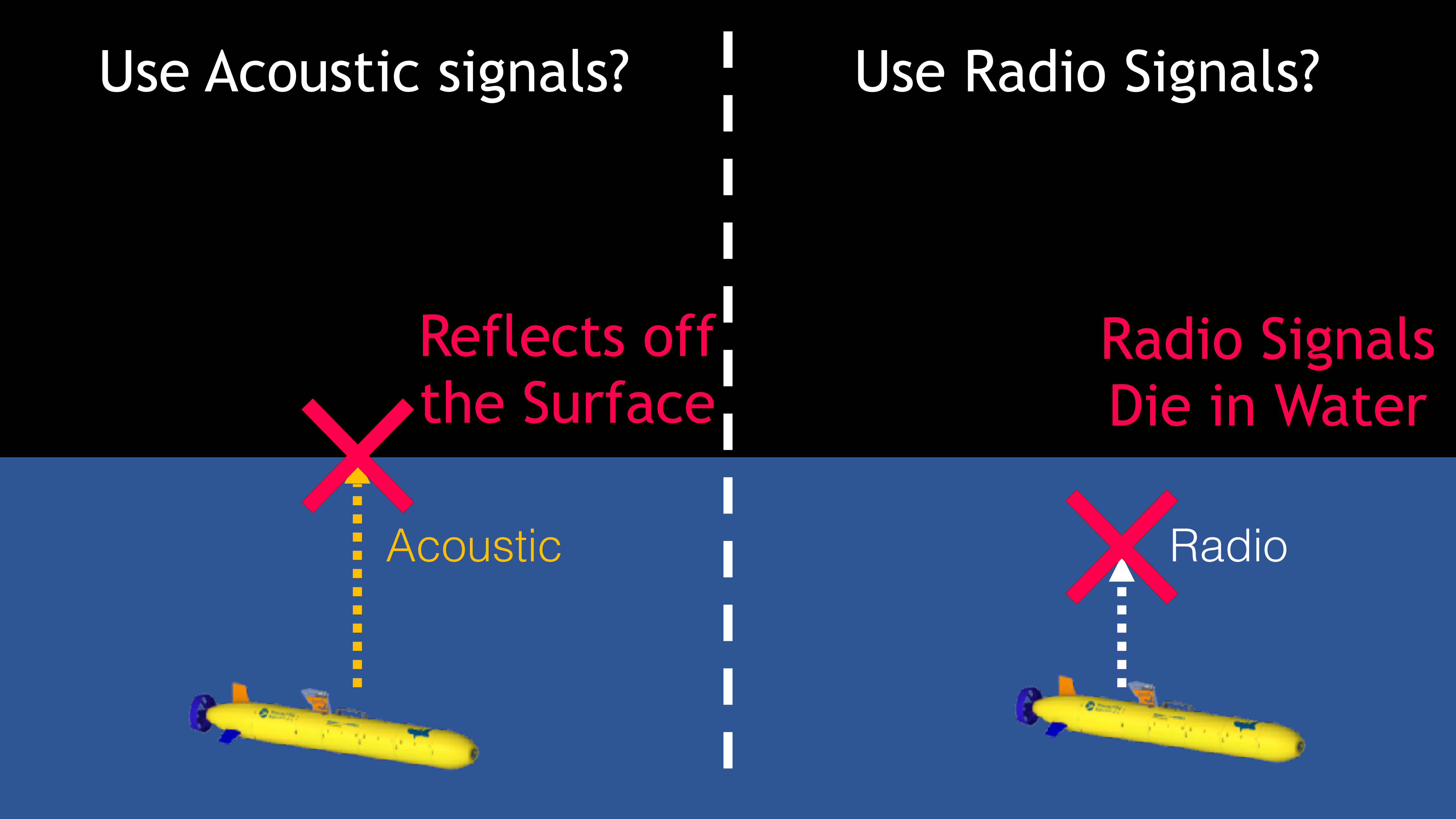
Wireless Signals Work Well Only in a Single Medium

Radio

Acoustic

or SONAR

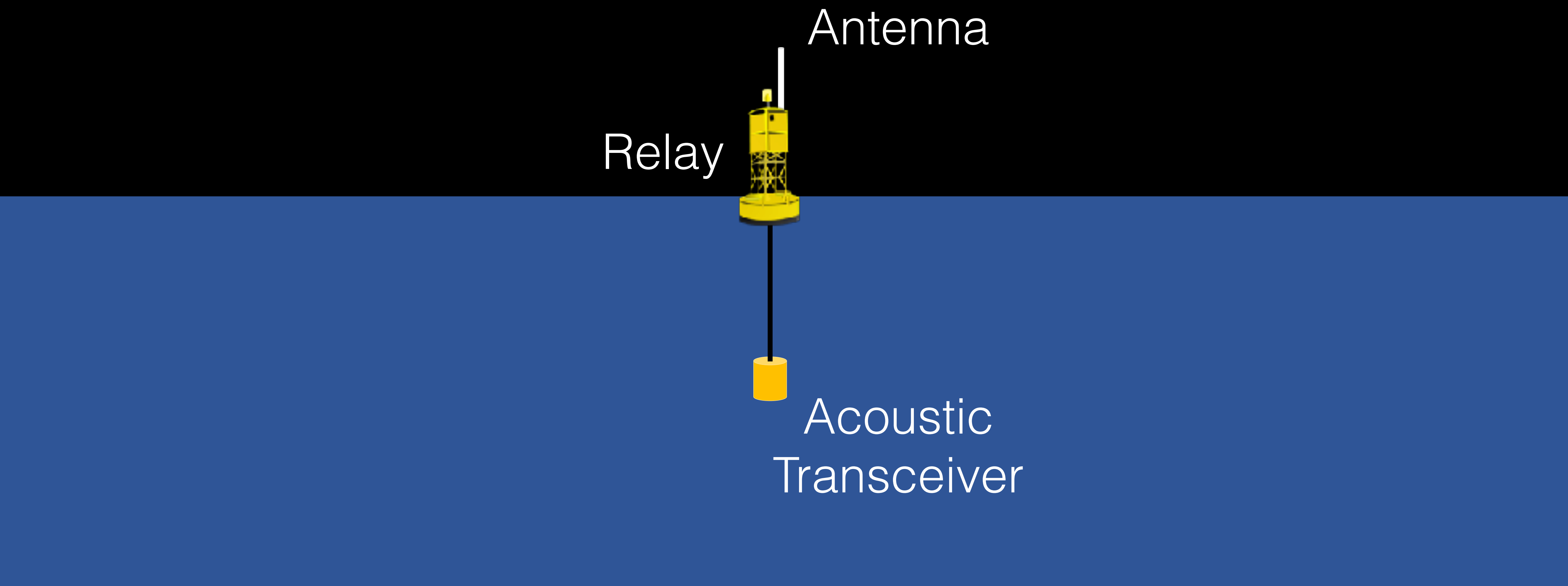

Use Acoustic signals?
Reflects off the Surface
Acoustic


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?

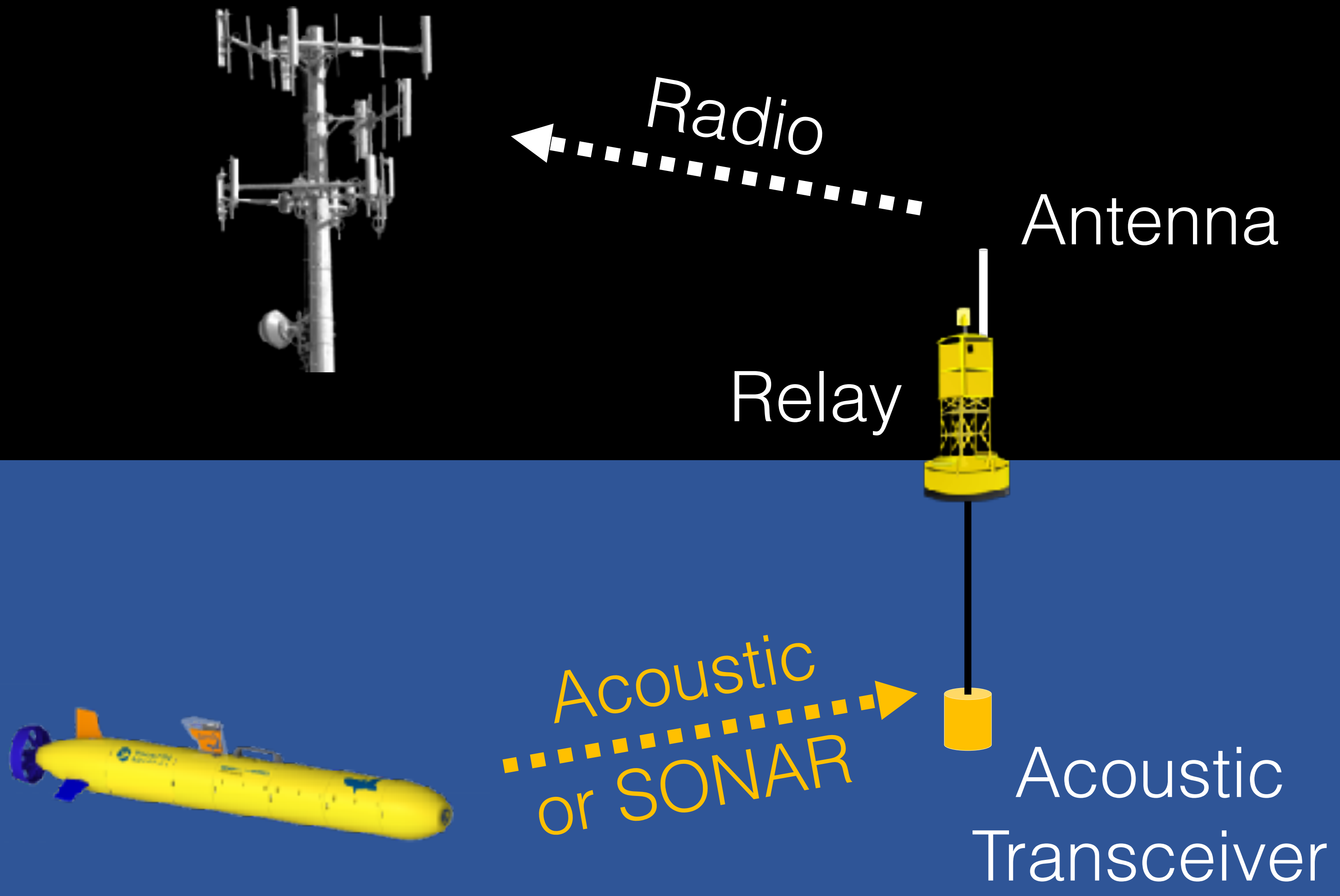
Approach #1: Relay Nodes

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



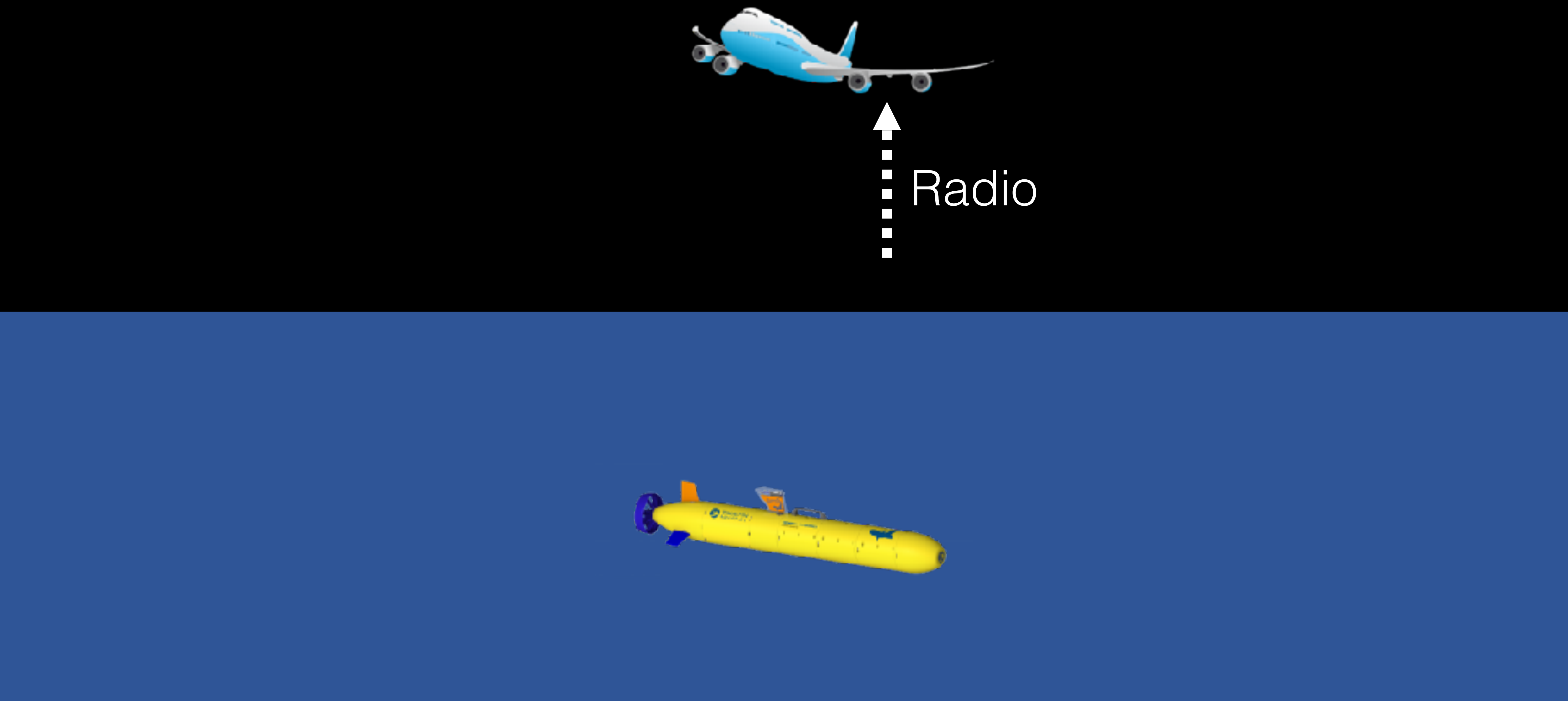
Approach #1: Relay Nodes

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



Approach #2: Surfacing

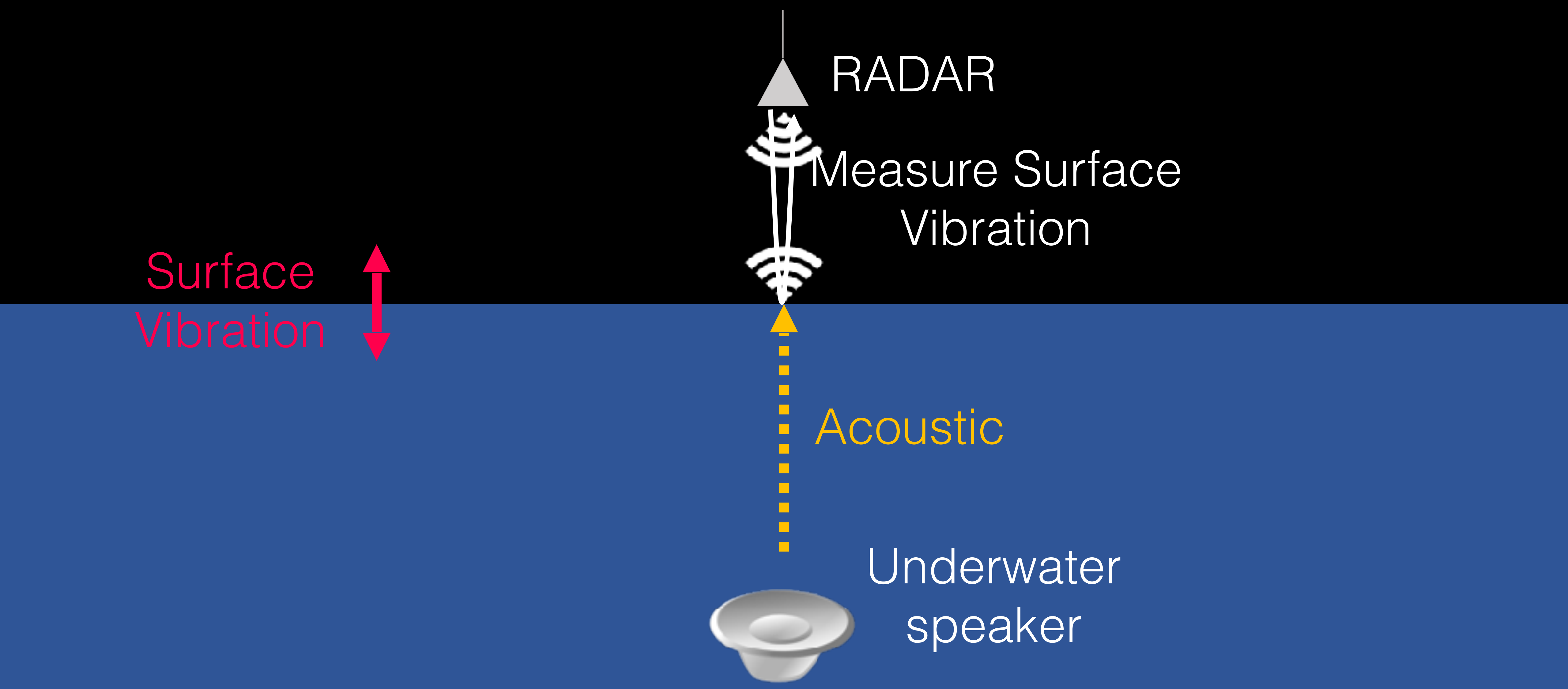
[ICRA'06, MOBICOM'07, OCEANS'10, ICRA'12]



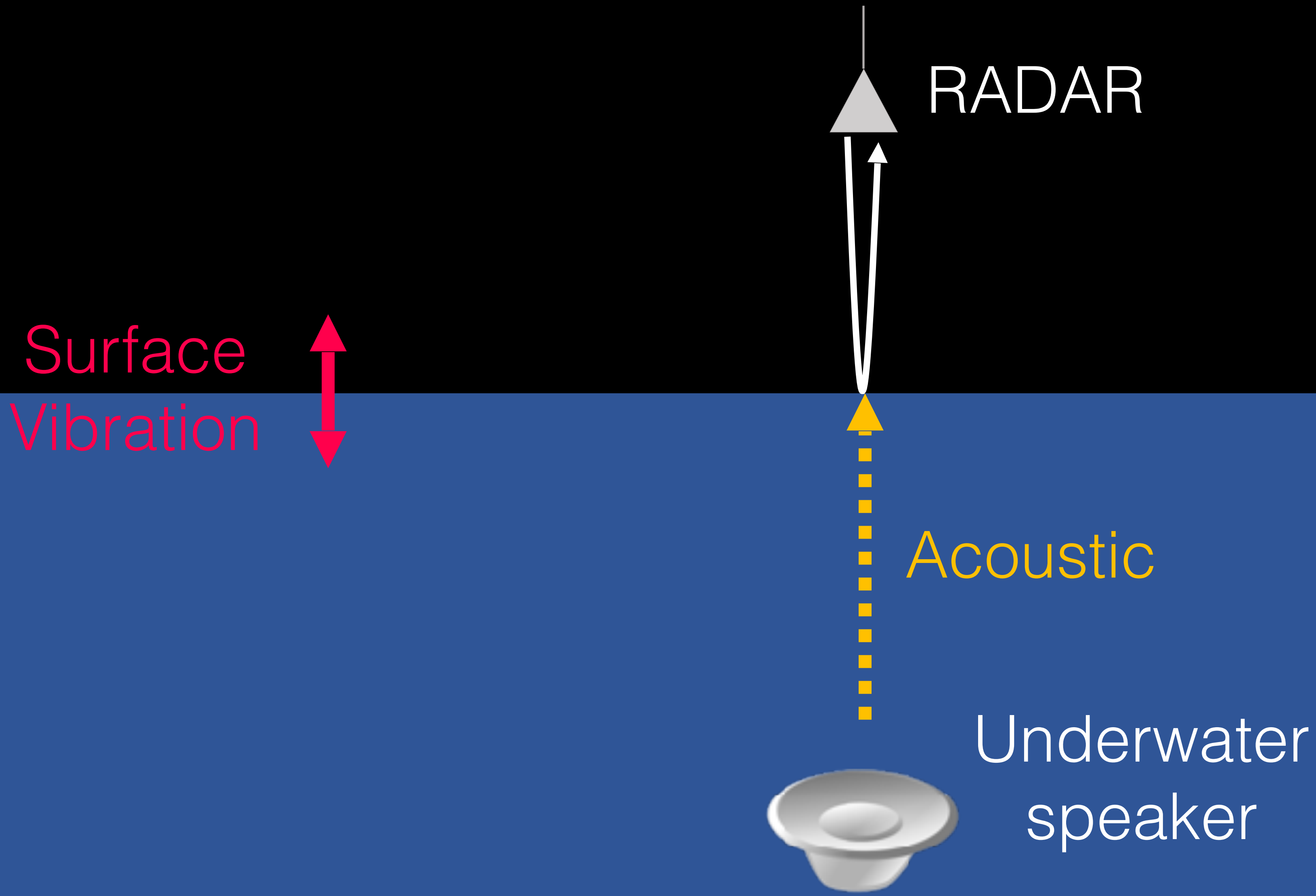
Technology that Enables Compact Sensors to Wirelessly Communicate Across the Water-Air Boundary

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

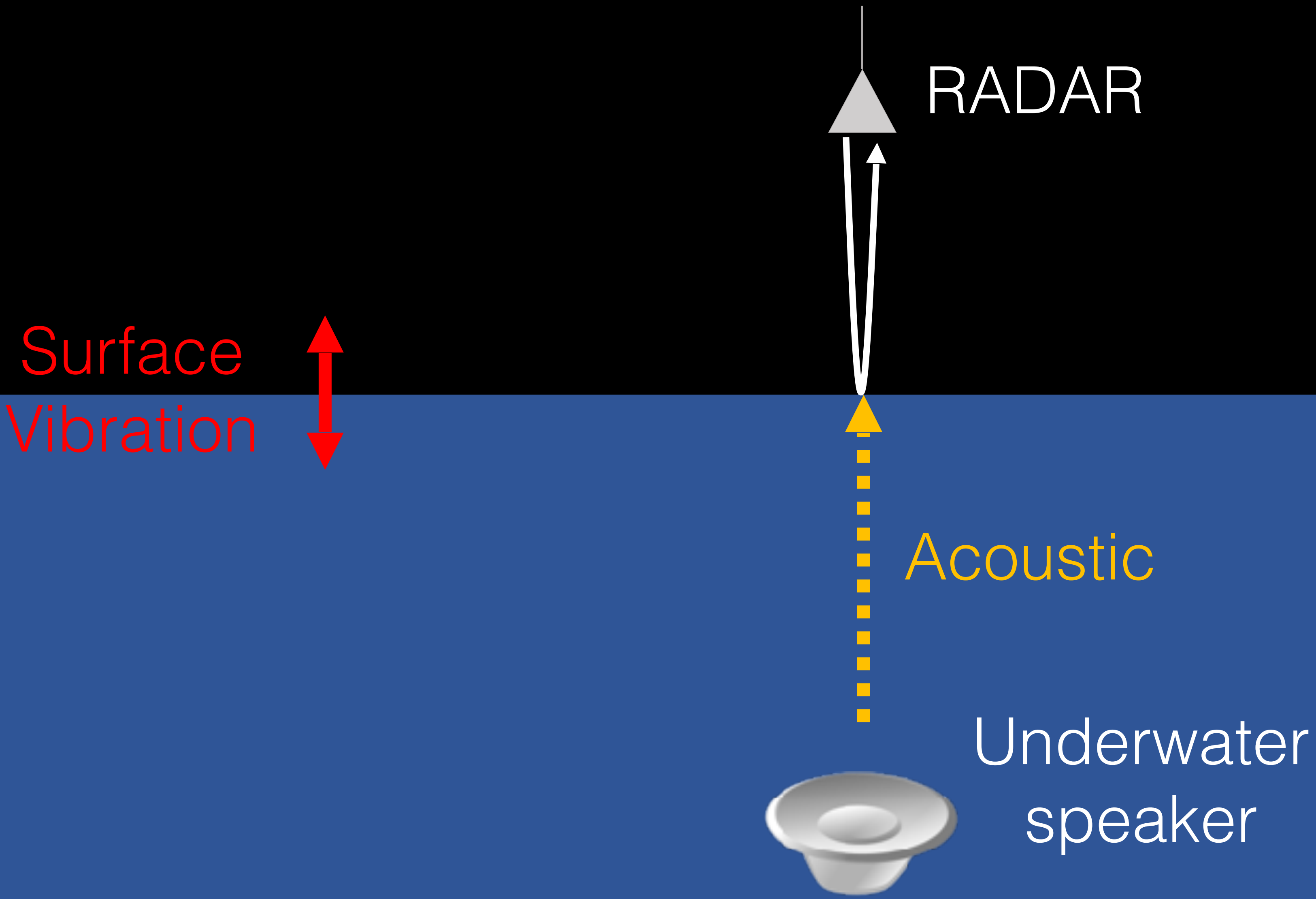
First technology that enables wireless communication across water-air interface

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

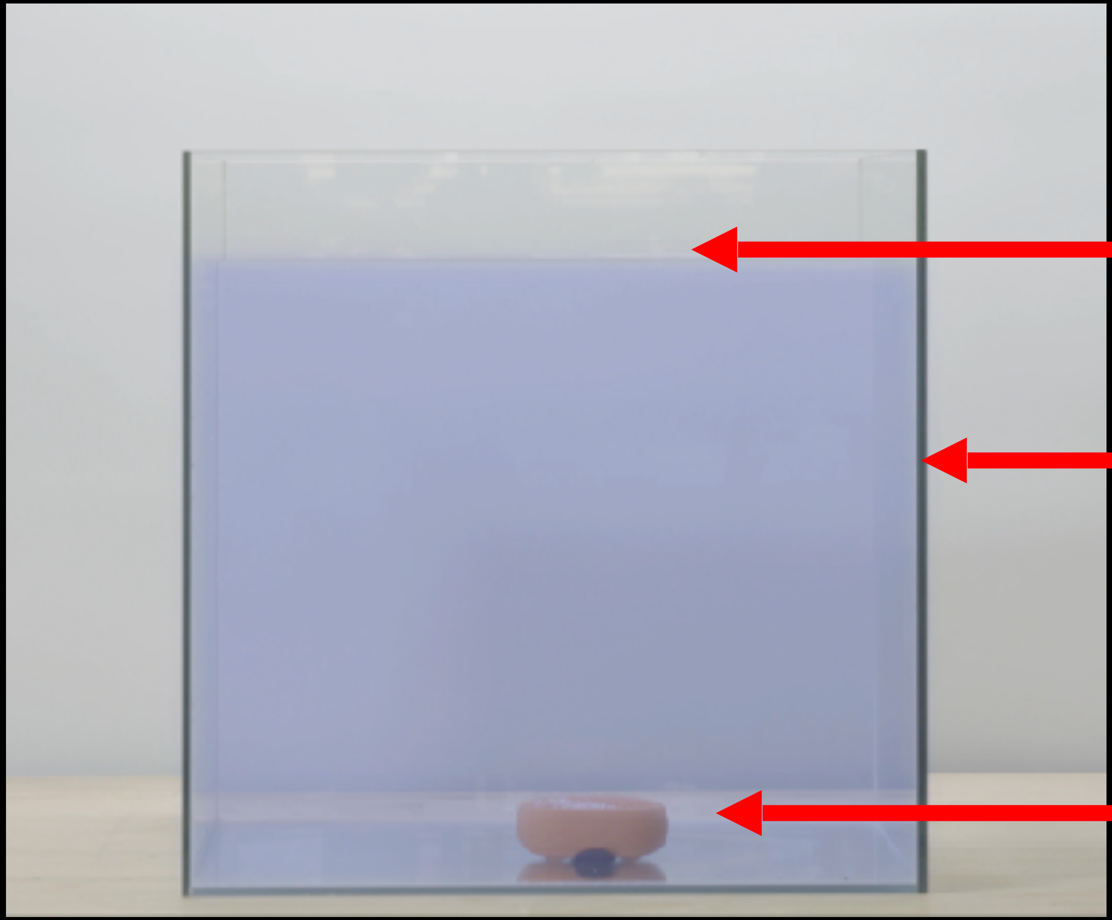
Key Idea



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

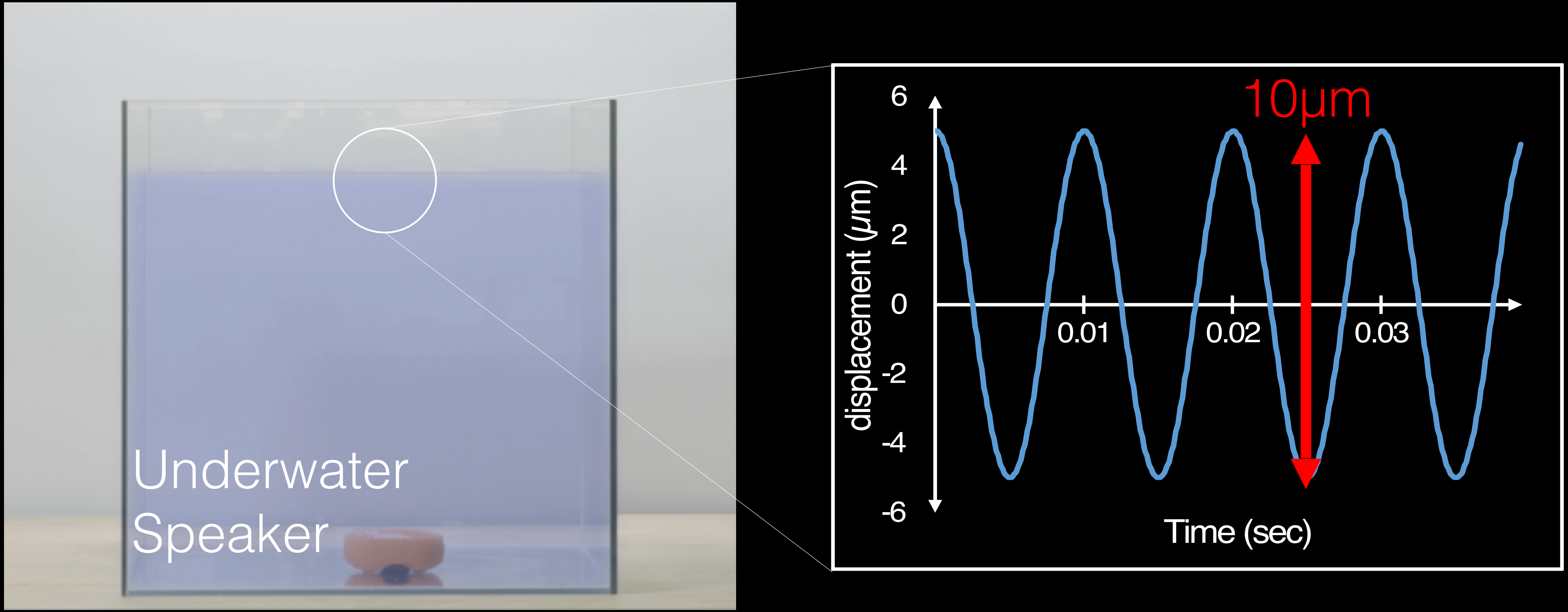
Recording the Surface Vibration

Experiment: Transmit Acoustic Signals at 100Hz



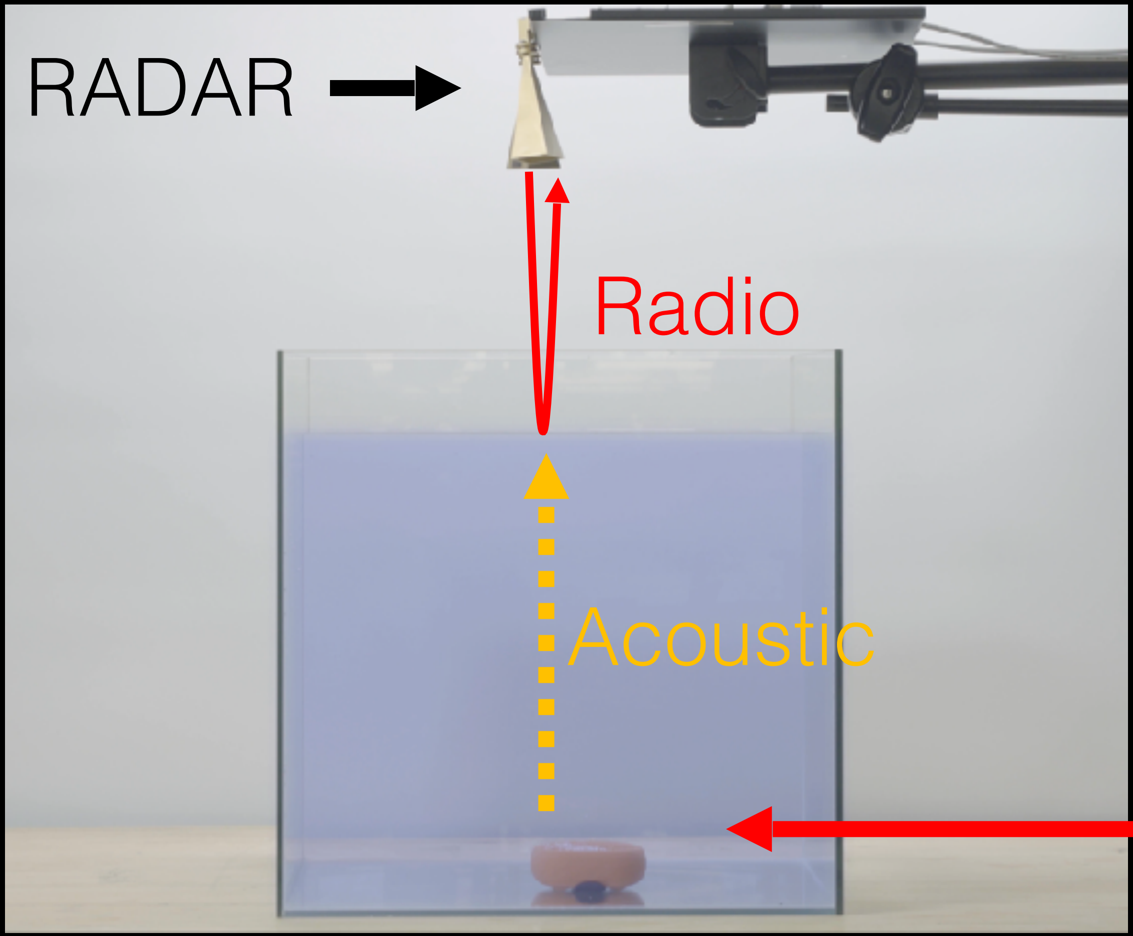
Recording the Surface Vibration

Experiment: Transmit Acoustic Signals at 100Hz



How Can We Sense Microscale Vibration?

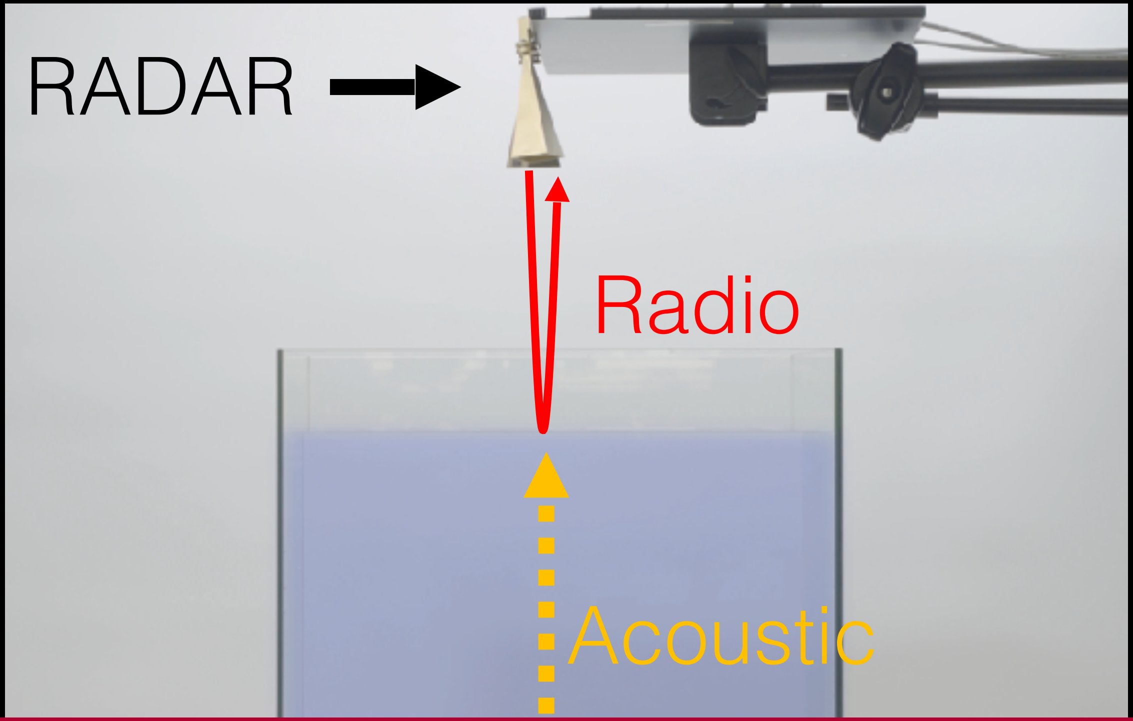
Idea: Use RADAR to measure the surface vibration



Underwater
Speaker

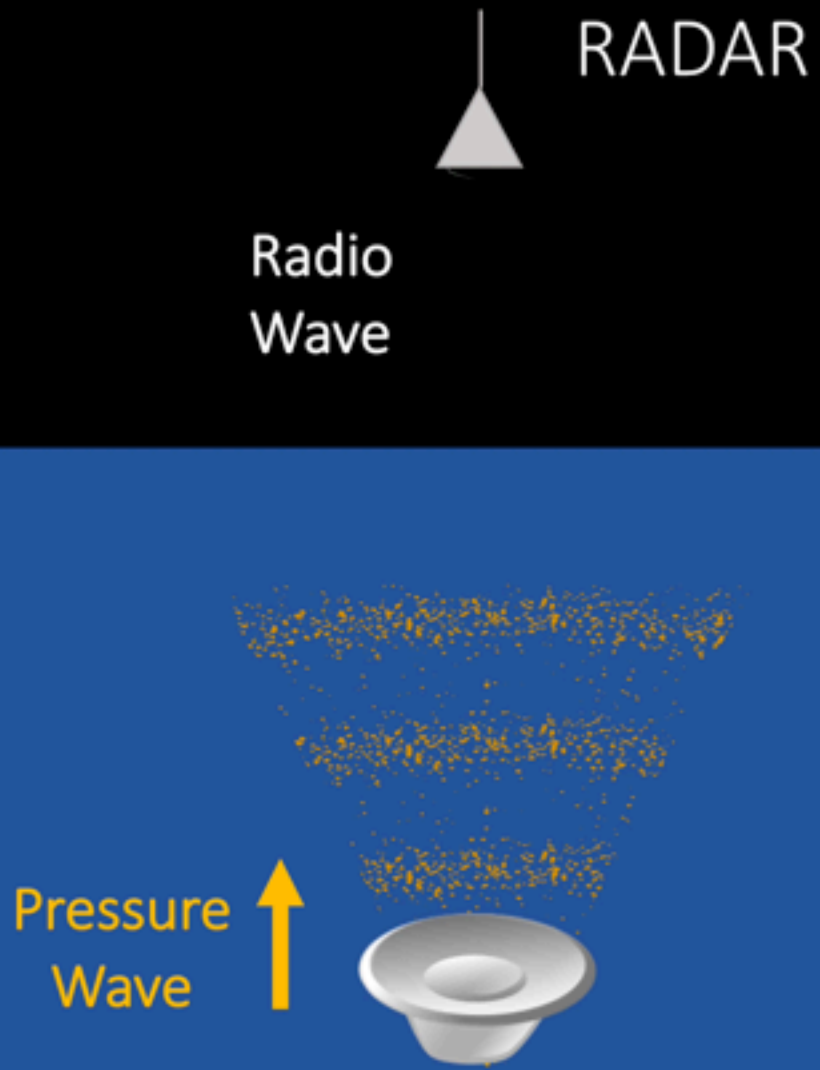
How Can We Sense Microscale Vibration?

Idea: Use RADAR to measure the surface vibration

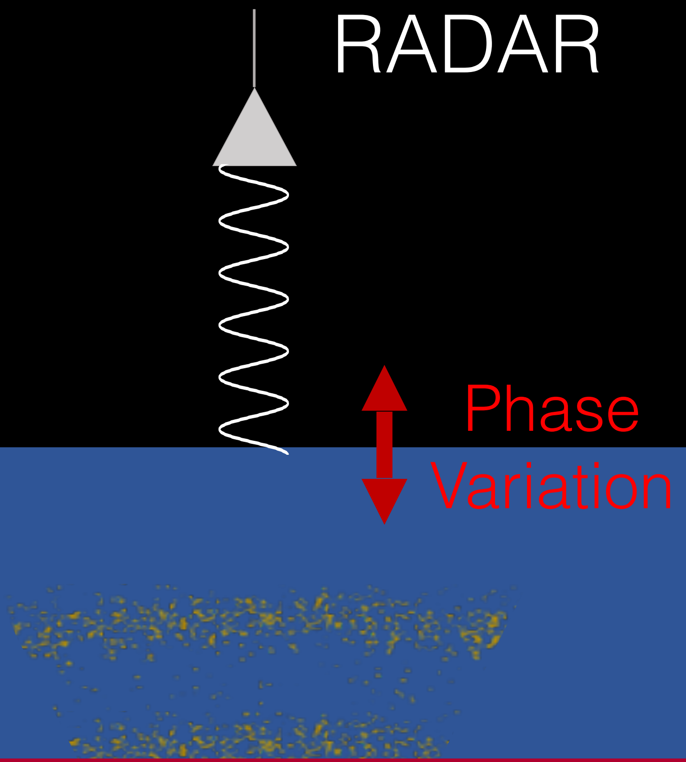


<u>Problem:</u> Measuring micrometer vibrations requires 100s of THz of bandwidth → Impractical & Costly

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



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



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

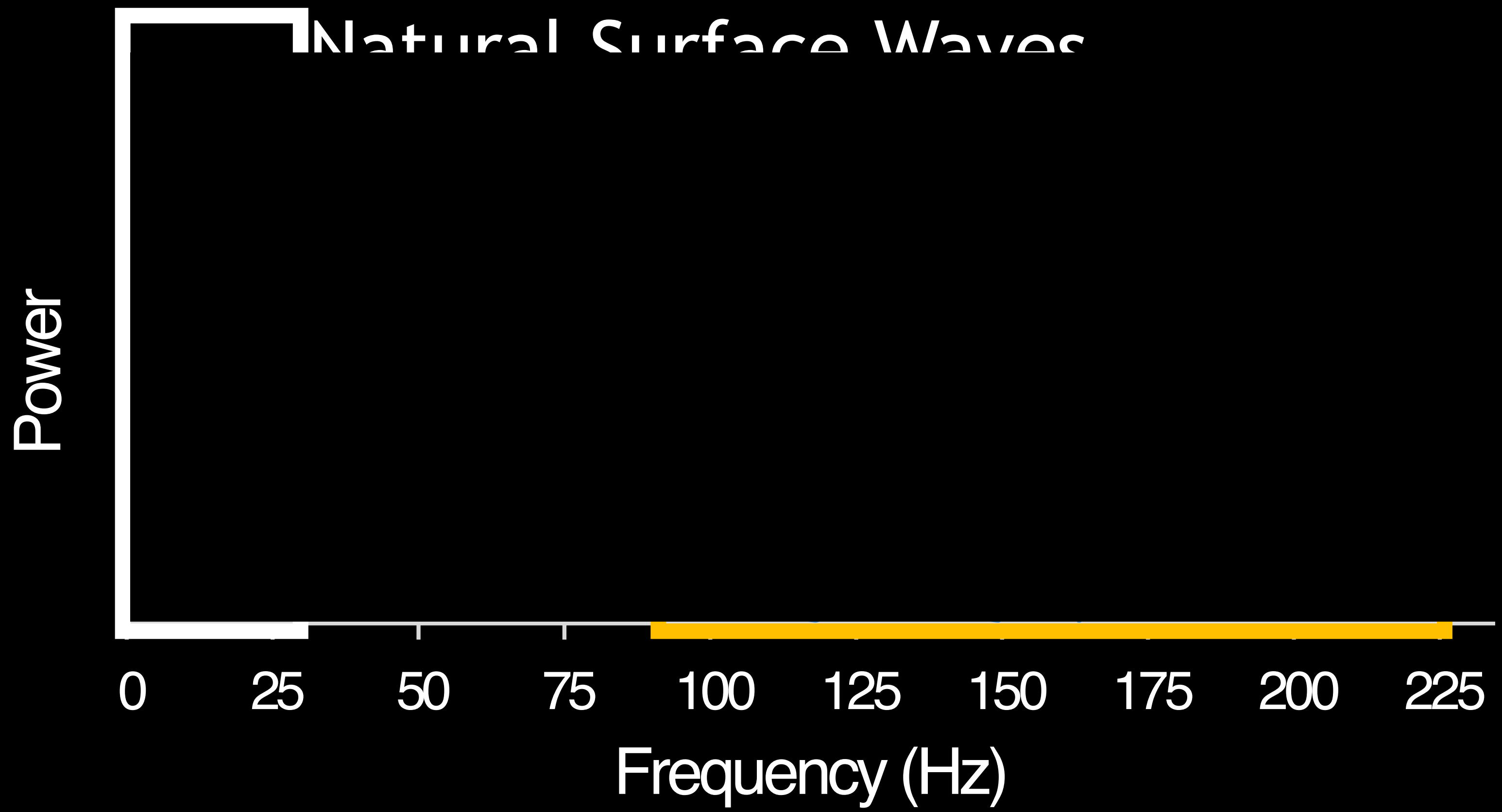
↓

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

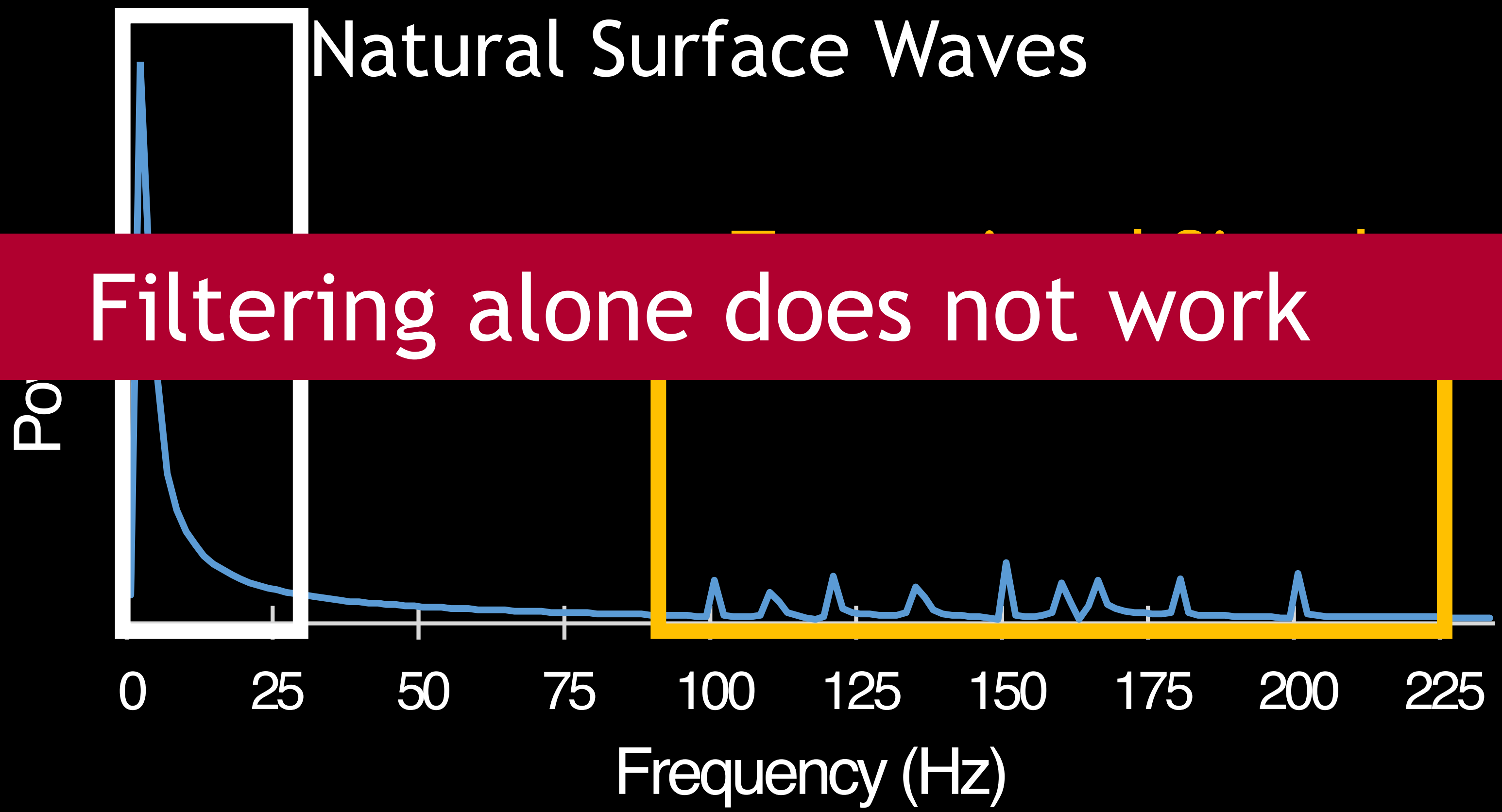
Natural Surface Waves Can Be Treated as Structured Interference and Filtered Out

	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



Dealing with Waves

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

Dealing with Waves

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

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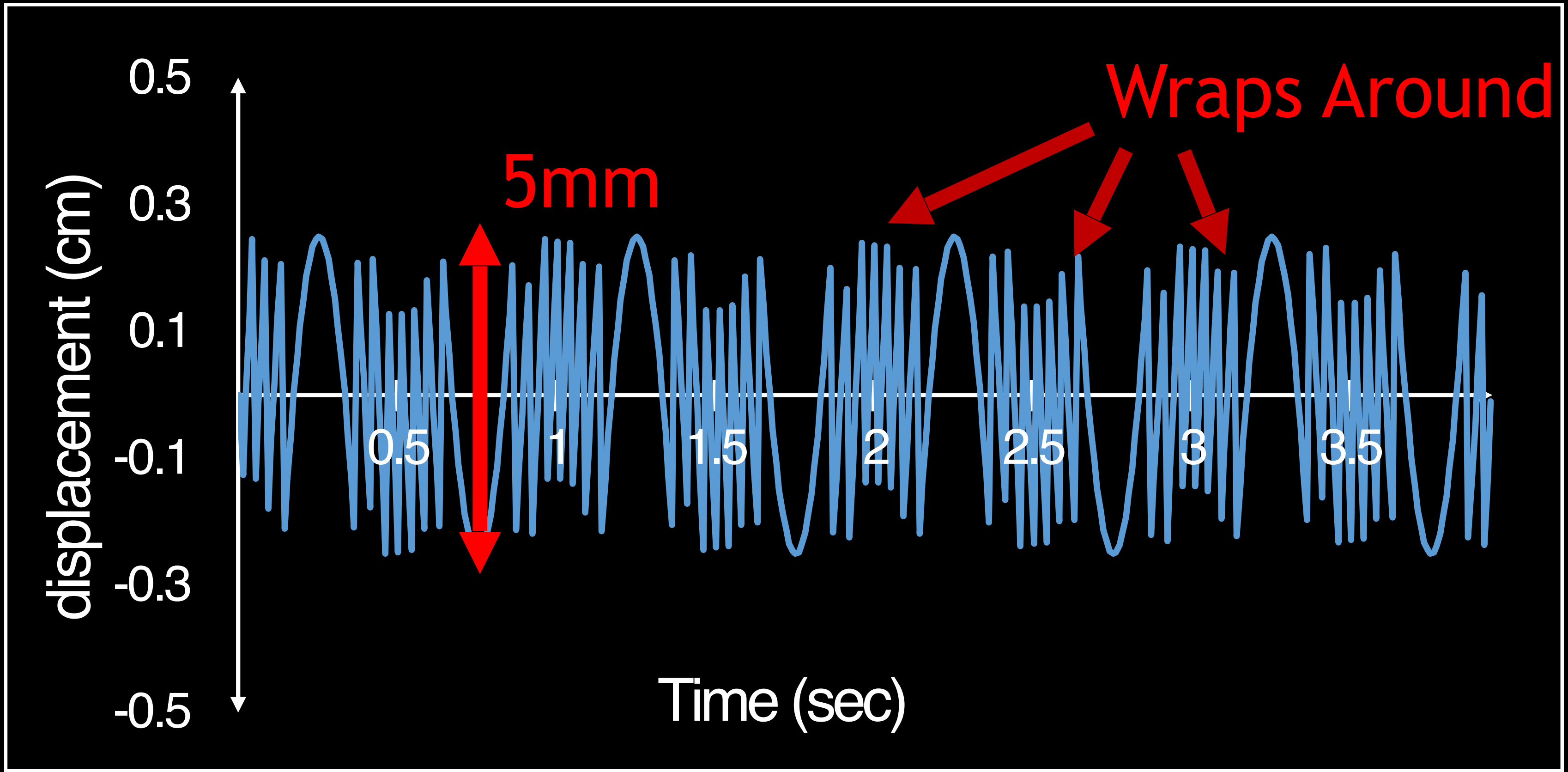
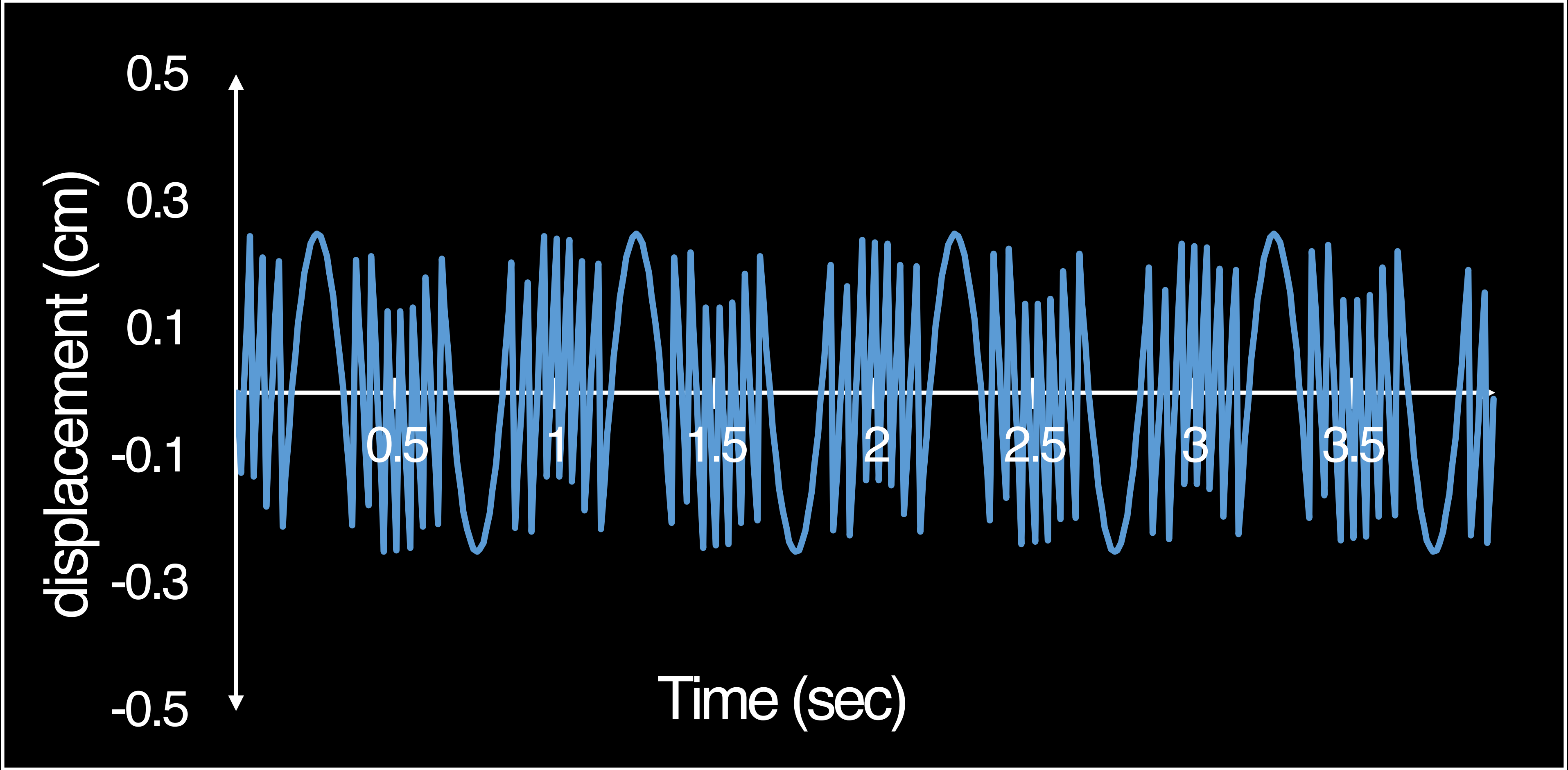
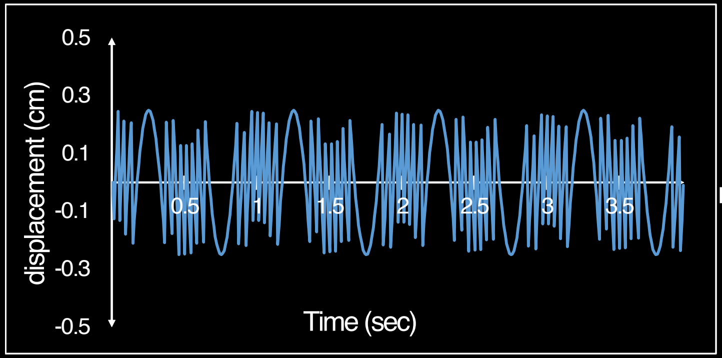


Dealing with Waves

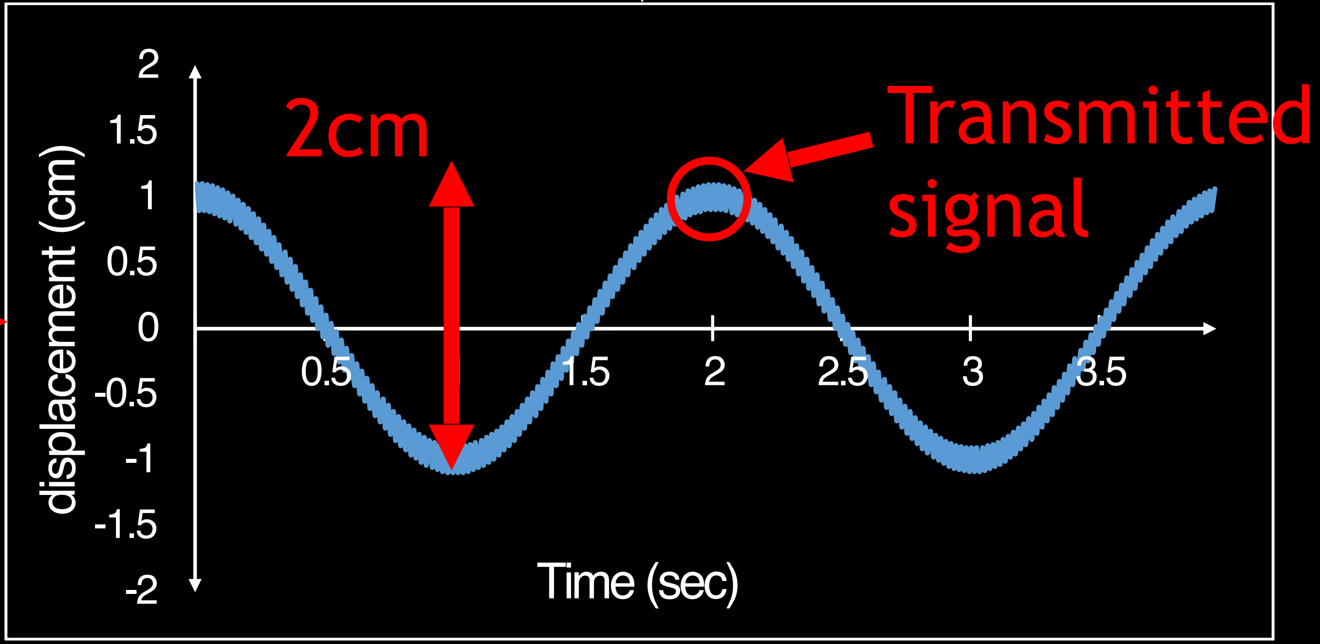


Dealing with Waves

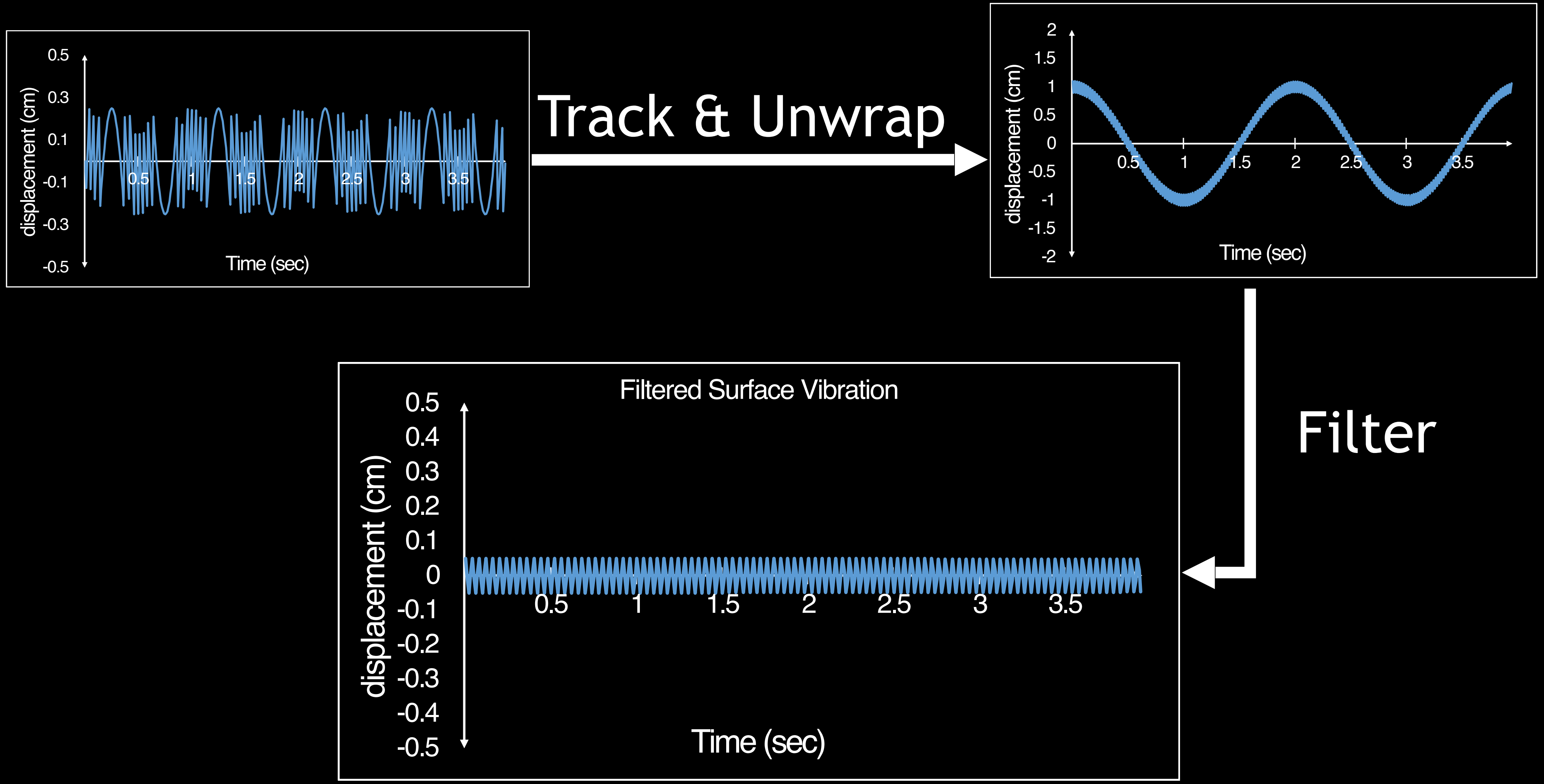


Track & Unwrap

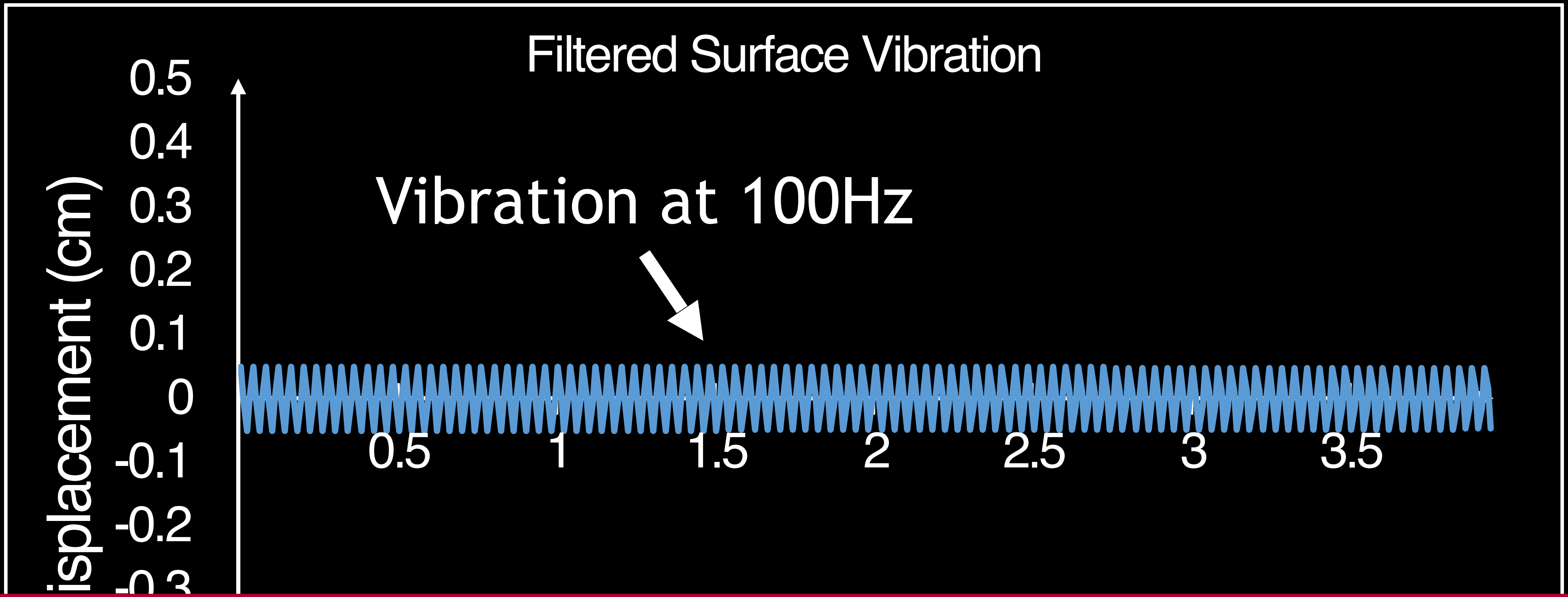
Trend is Water Surface Wave



Dealing with Waves

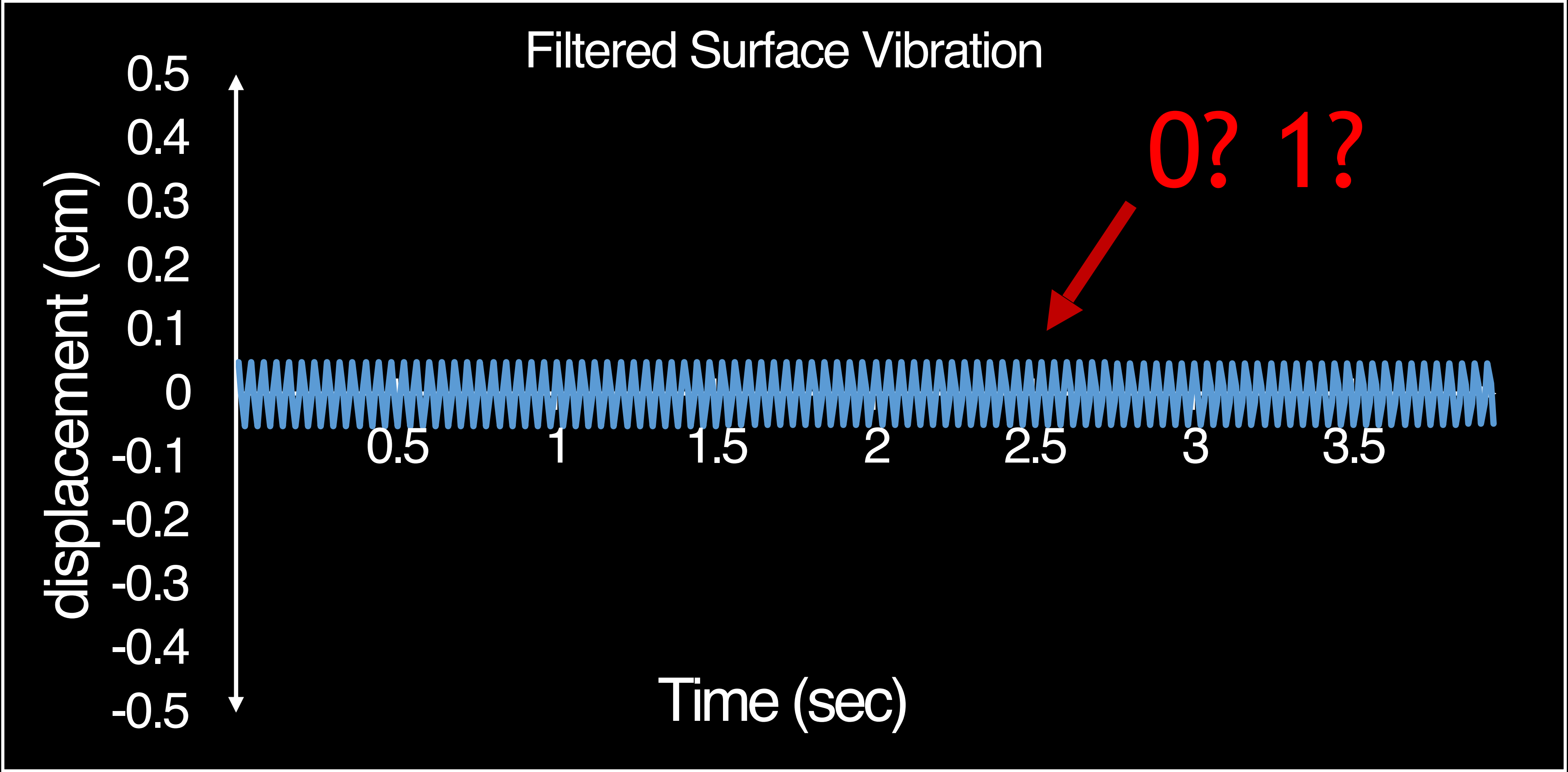


Dealing with Waves



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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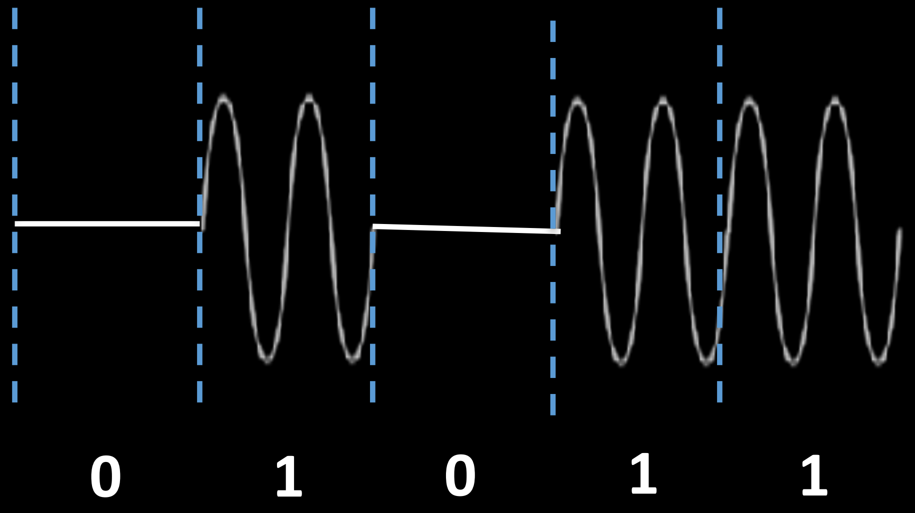
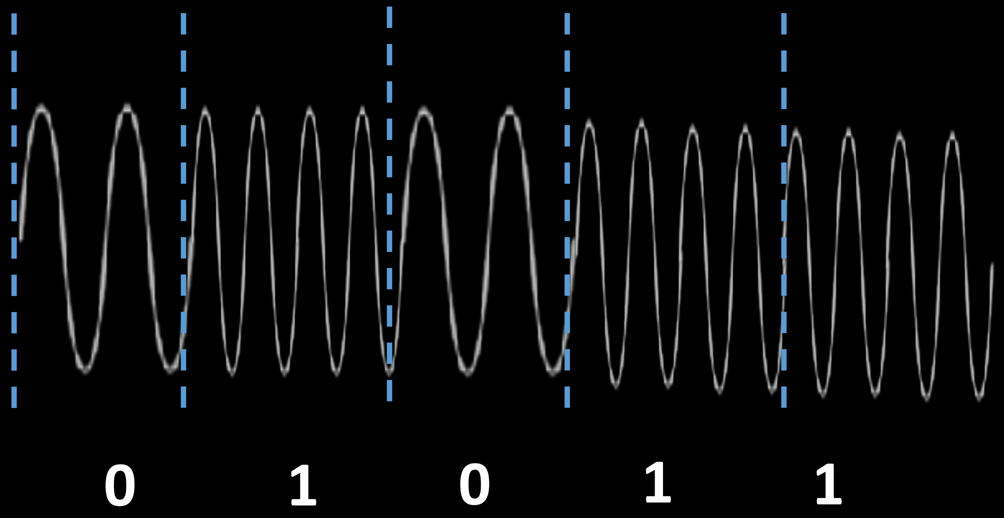
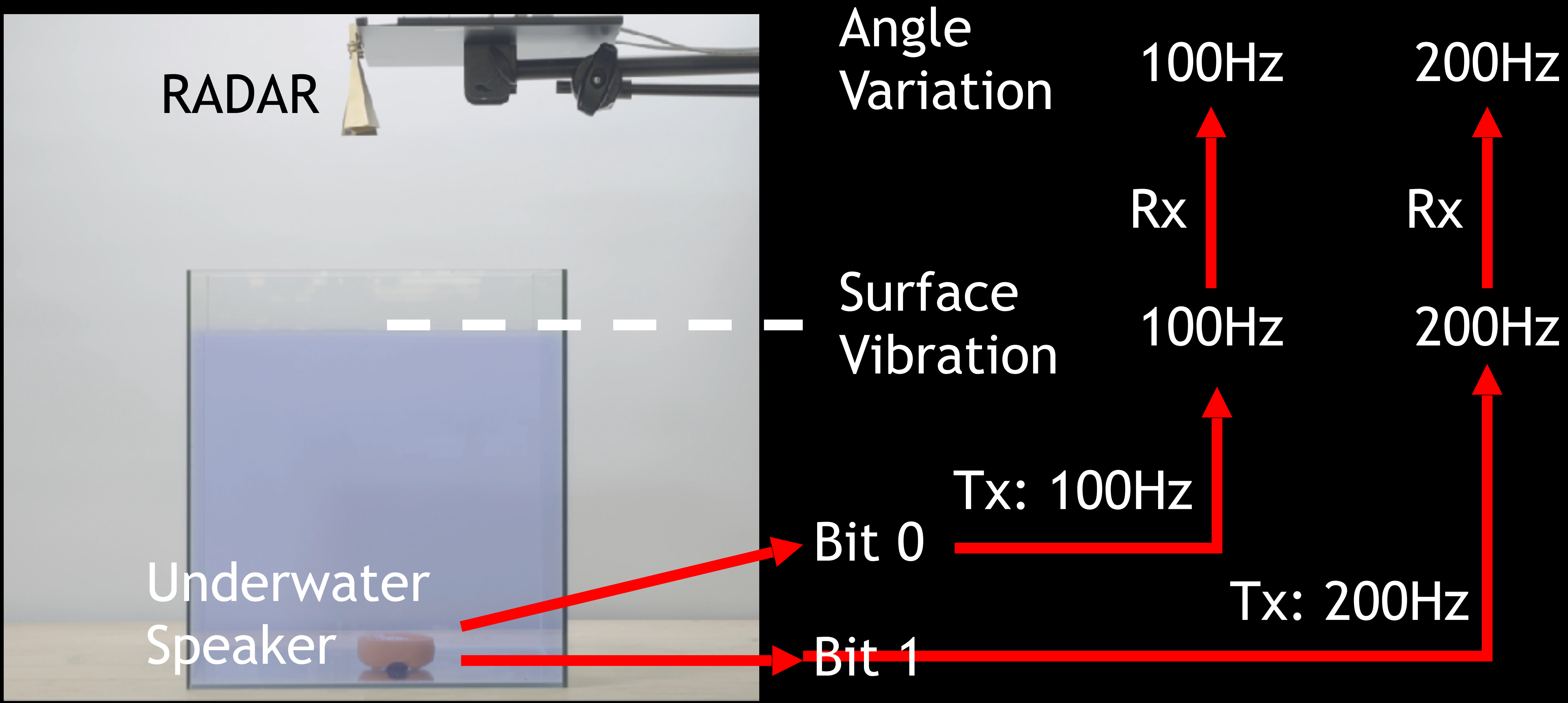


On – Off Keying



Frequency shift keying (FSK)

Decoding Information



Standard Modulation Schemes?

The wireless channel

Mathematics & Physical Interpretation

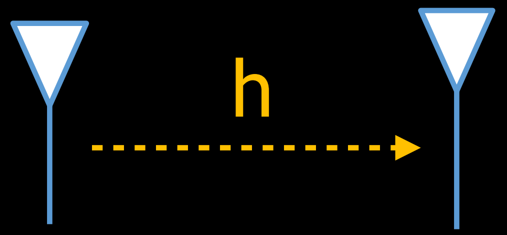
Upconversion & Downconversion

Modulation & Demodulation

The Wireless Channel (Math)

Complex number, I/Q plane, example

Tx Rx



x $y = hx$

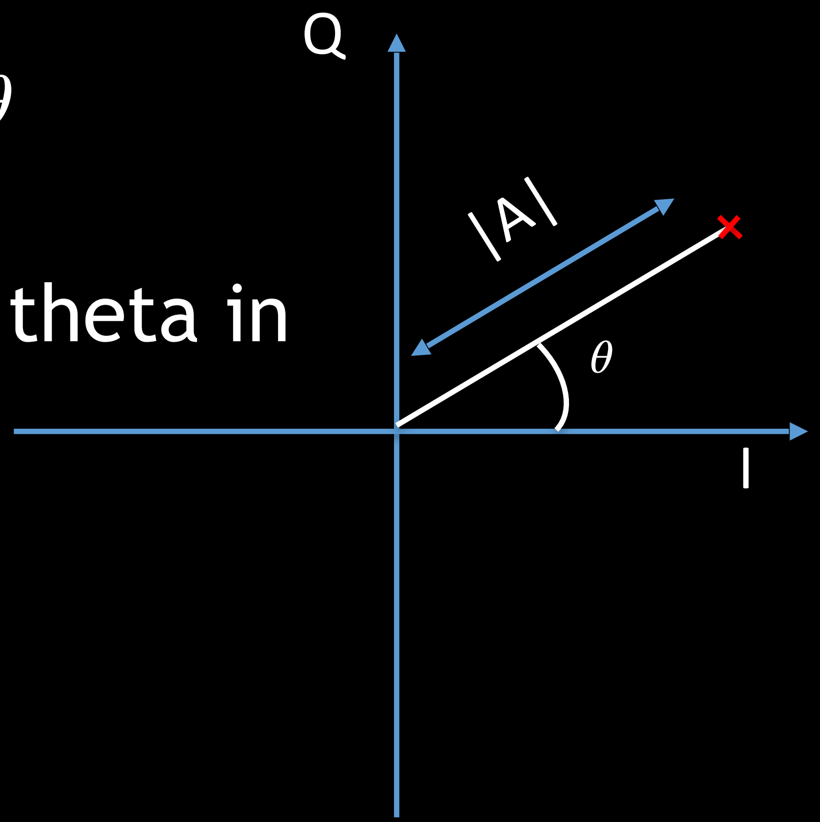
Rx channel Tx

(a complex number)

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

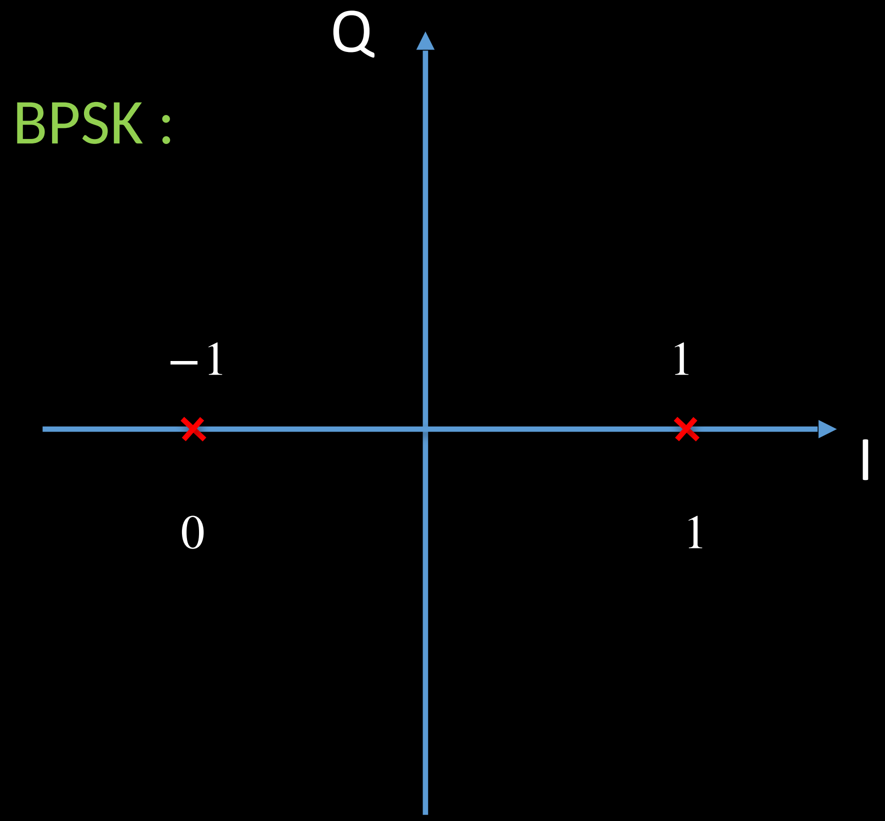
Bits	0	1	1	0	0
Symbols = X	-1	+1	+1	-1	+1
Y = hX	-1/4-1/4j	1/4+1/4j	1/4+1/4j	-1/4-1/4j	1/4+1/4j
Decoded Symbols = X'	-1	+1	+1	-1	+1
Decoded bits	0	1	1	0	0

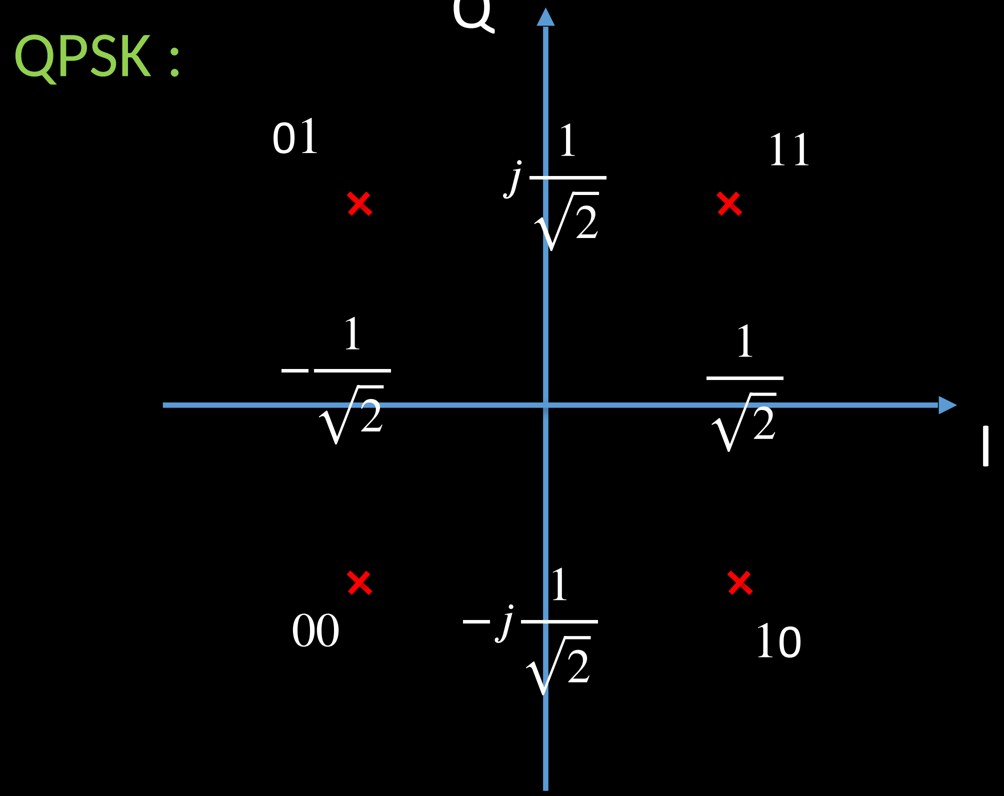
How can I estimate the channel?

Pros/Cons of long vs short preamble?

Modulation Schemes

Bits -> Complex number



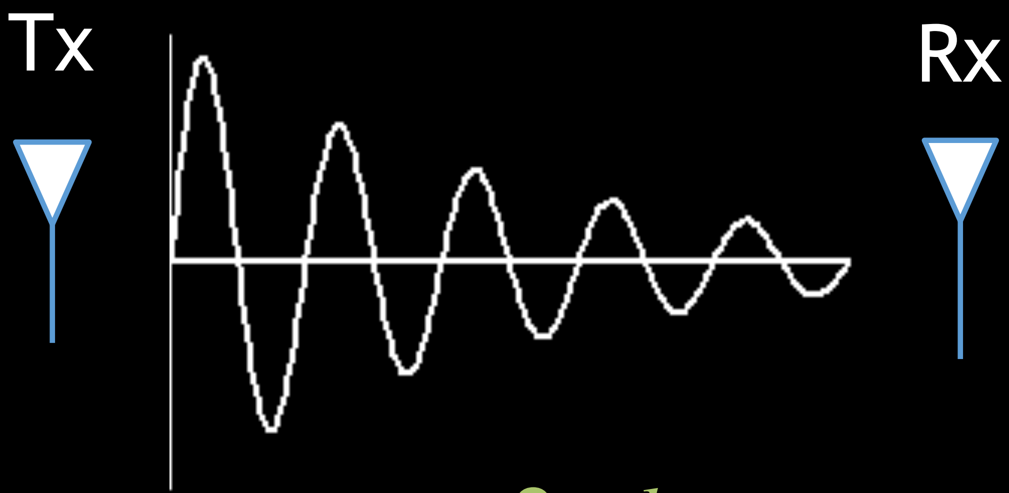


Pros/Cons of BPSK vs QPSK?

other modulation schemes?

The Wireless Channel (Physics)

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



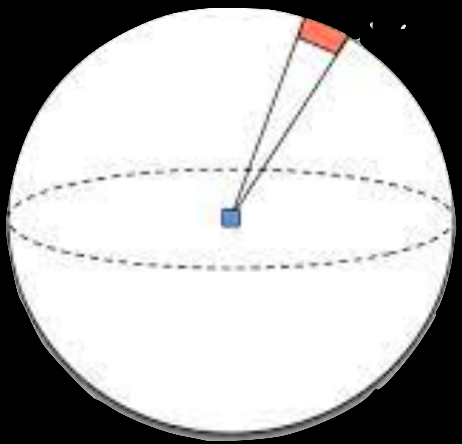
- Transmit a cosine (at frequency)
  why can't transmit without cosine?

- What is the channel?

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

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

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



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

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

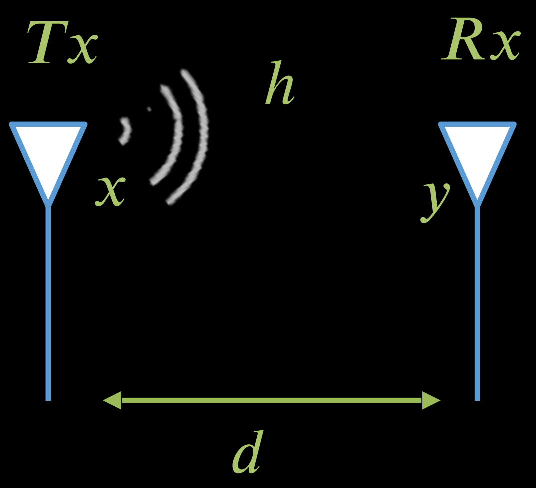
$$h = \frac{1}{d}e^{j\frac{2\pi d}{\lambda}}$$

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 (symbols)

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

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

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

Extensions

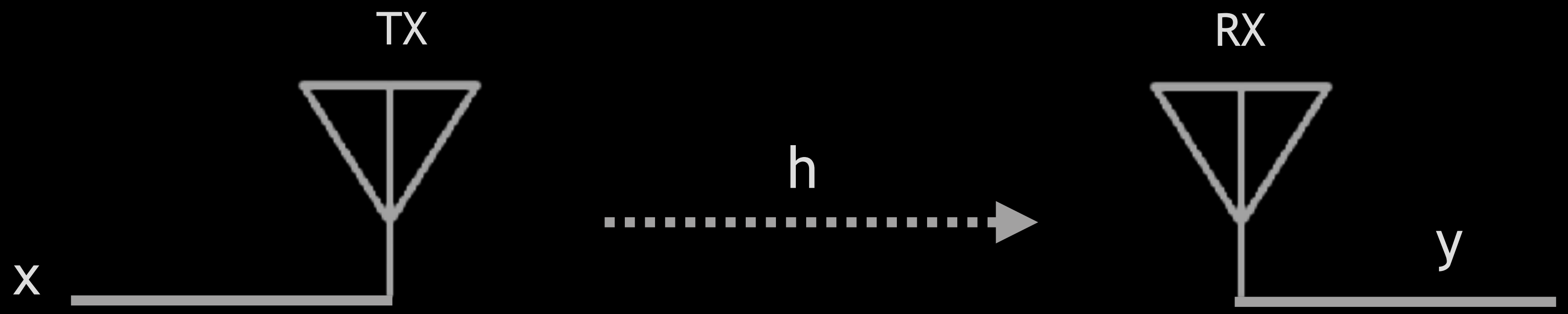
Can Tx more frequencies, highest possible rate?

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

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

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

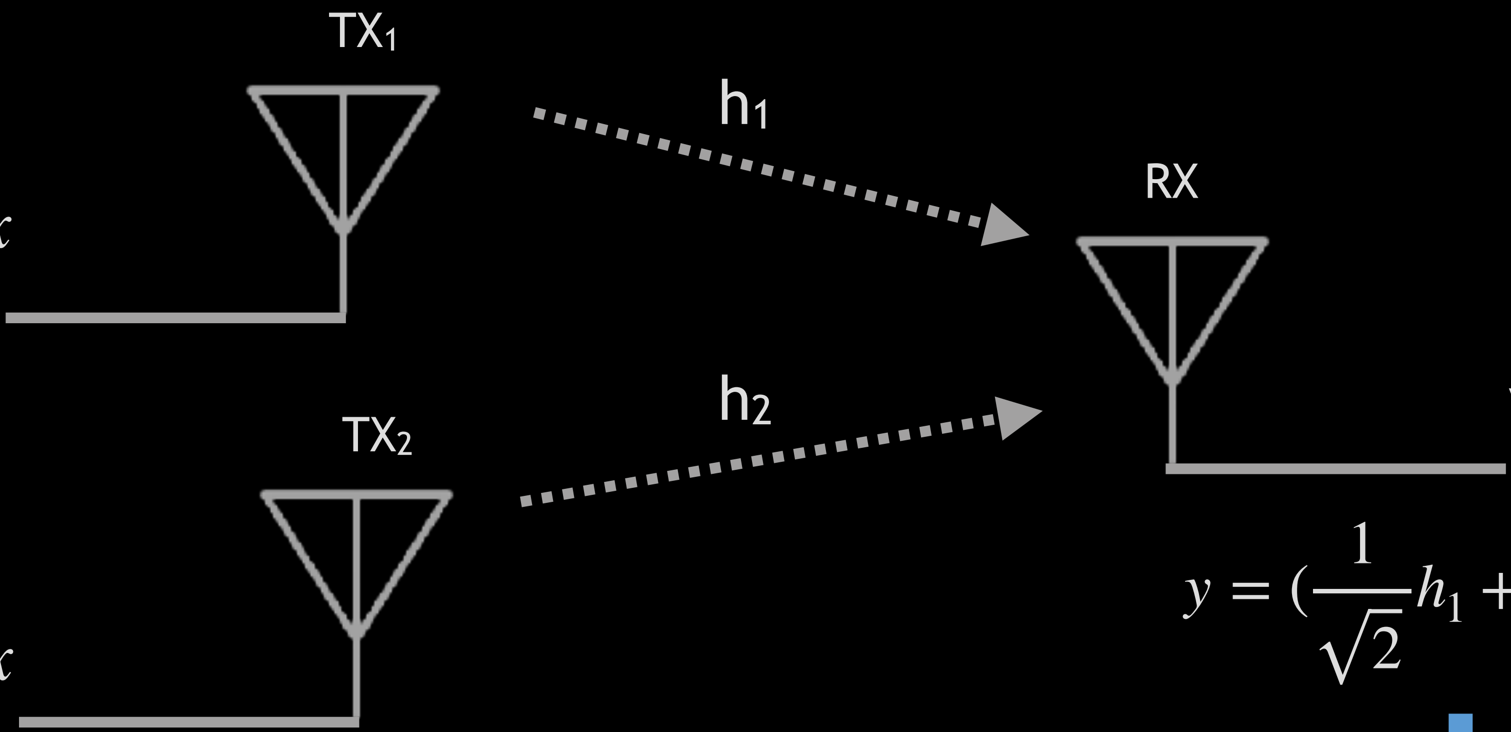
$$\text{SNR} = \frac{P_{tx}|h|^2}{|n|^2} \approx \frac{|h|^2}{|n|^2}$$

Same power, divided across 2 ants

Assume same channel, P_Rx=?, why?

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

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



$y = h_1x_1+h_2x_2+n$

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

$$h_1 = h_2 = h$$

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

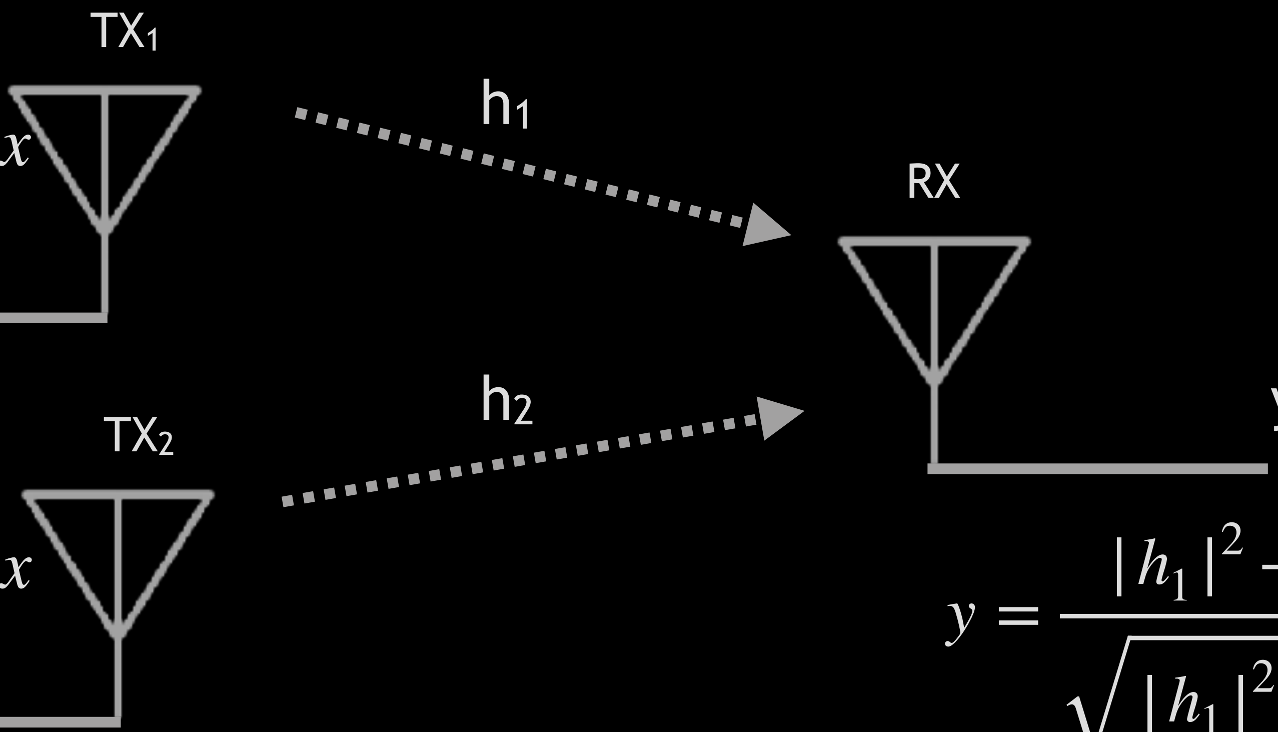
$$P_{rx} = 2|h|^2 P_{tx}$$

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

More realistic channels: how to precode?

Assume h1 different h2, where to Tx more power?

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



y = $h_1 x_1 + h_2 x_2 + n$

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

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

Maximal Ratio Combining

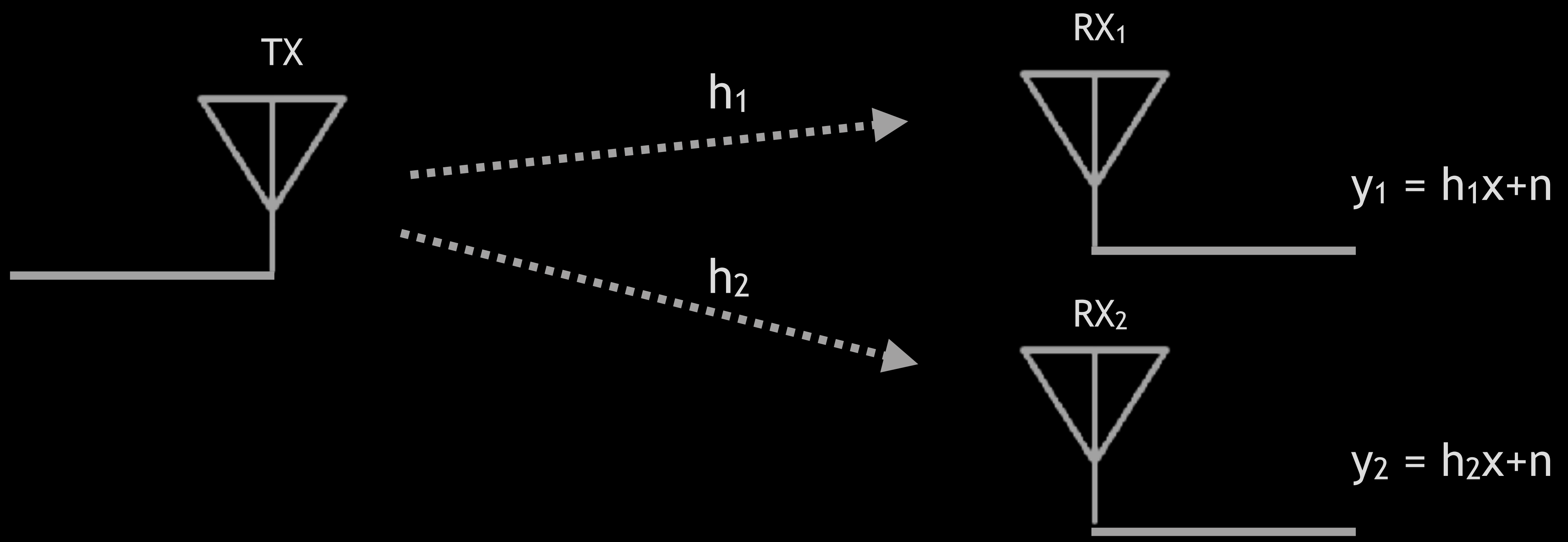
$$y = \sqrt{|h_1|^2 + |h_2|^2}\, x + n$$

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

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

Rx multi-antenna diversity

Two Rx's, how to combine?

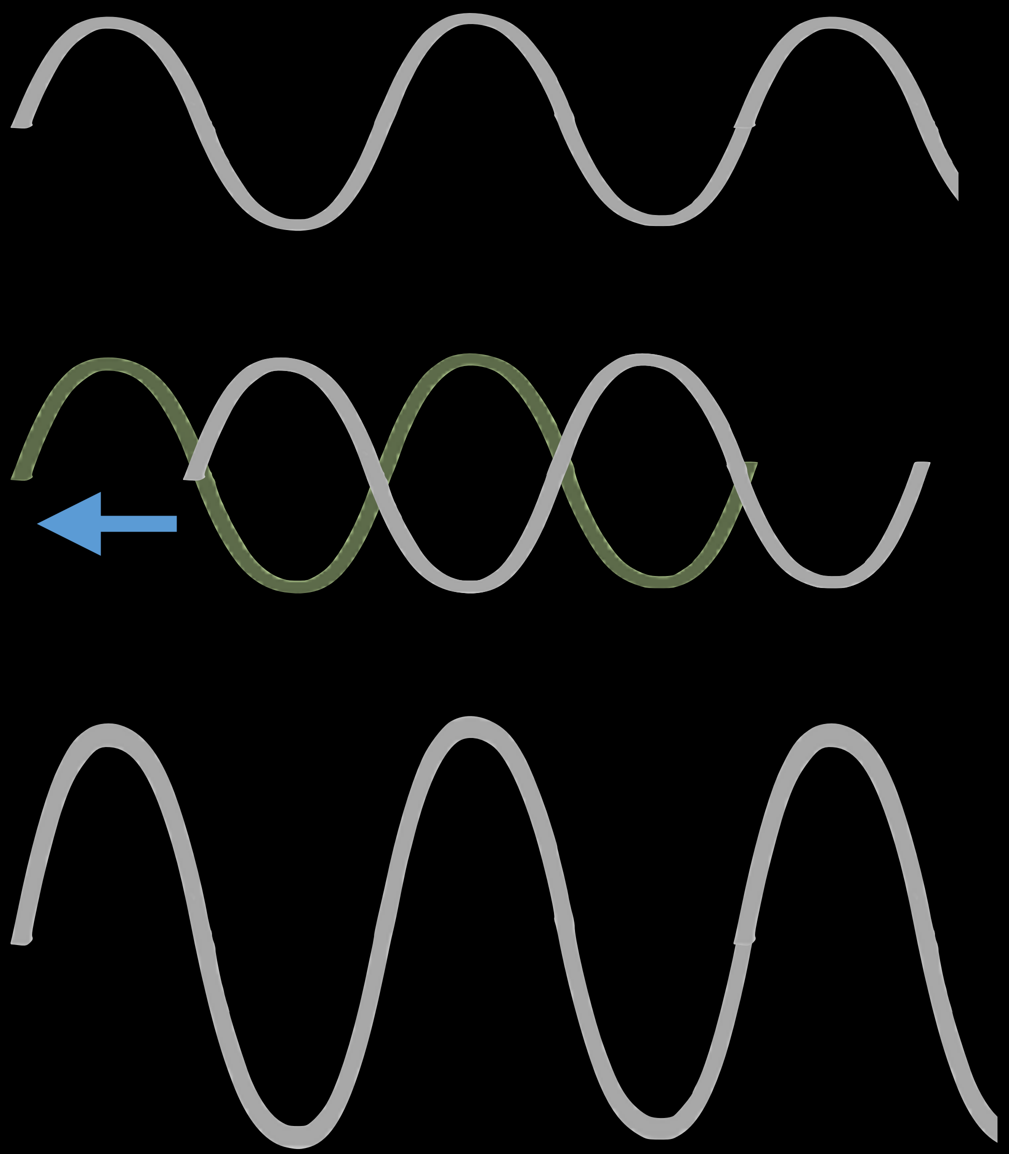


$$y = \frac{h_1^* y_1 + h_2^* y_2}{\sqrt{|h_1|^2 + |h_2|^2}} = \frac{h_1^*(h_1 x + n) + h_2^*(h_2 x + n)}{\sqrt{|h_1|^2 + |h_2|^2}} = \frac{(|h_1|^2 + |h_2|^2)x + (h_1^* + h_2^*)n}{\sqrt{|h_1|^2 + |h_2|^2}}$$

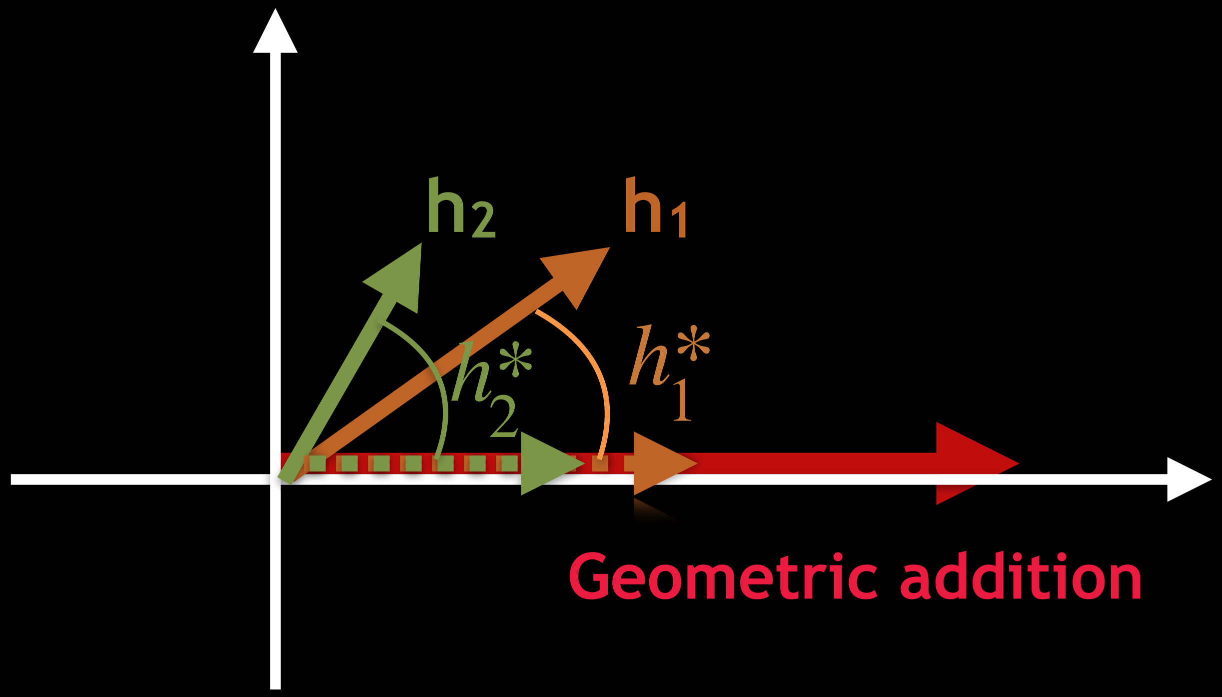
$$P_{rx} = (|h_1|^2 + |h_2|^2)P_{tx}$$

Interpretation of pre-coding

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

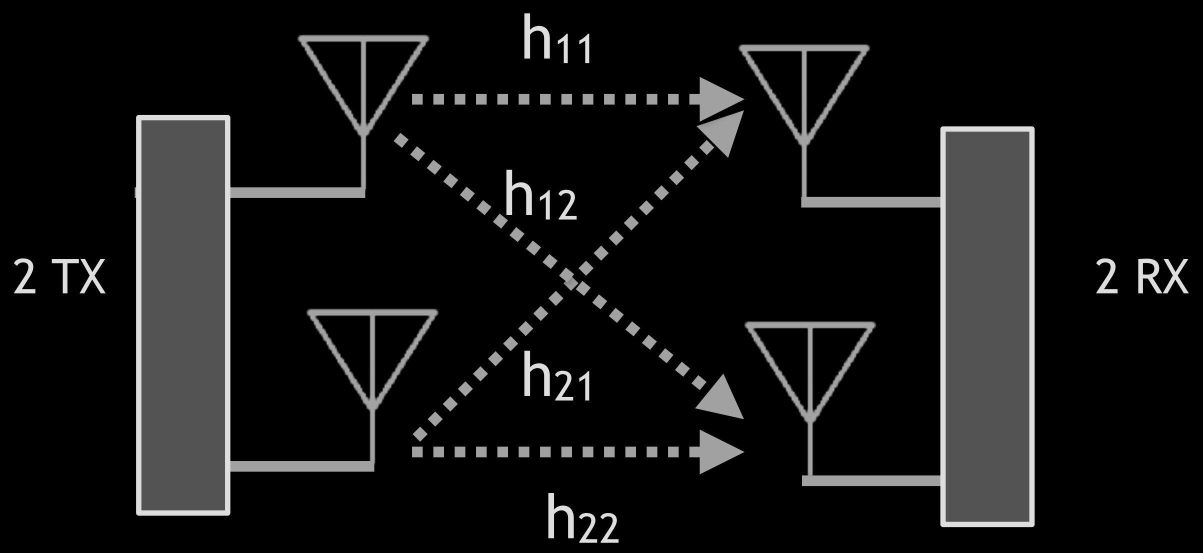


Sum:



Extension to MIMO

high-level diagram, diversity gain



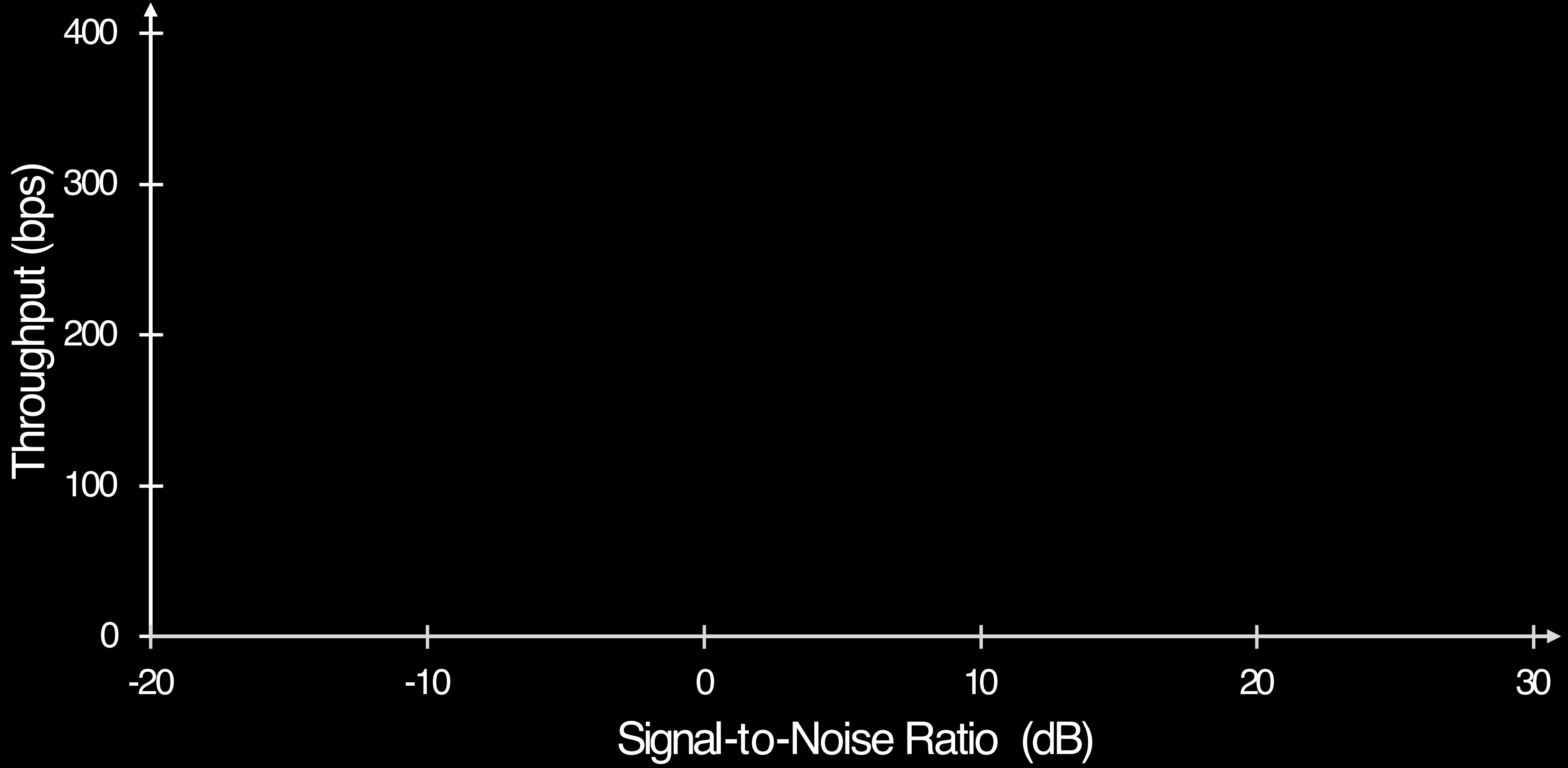
Gain for Diversity

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

Let’s go back to TARF

Throughput Results

Experiment: Vary the Power and Depth of Underwater Transmission



Throughput Results

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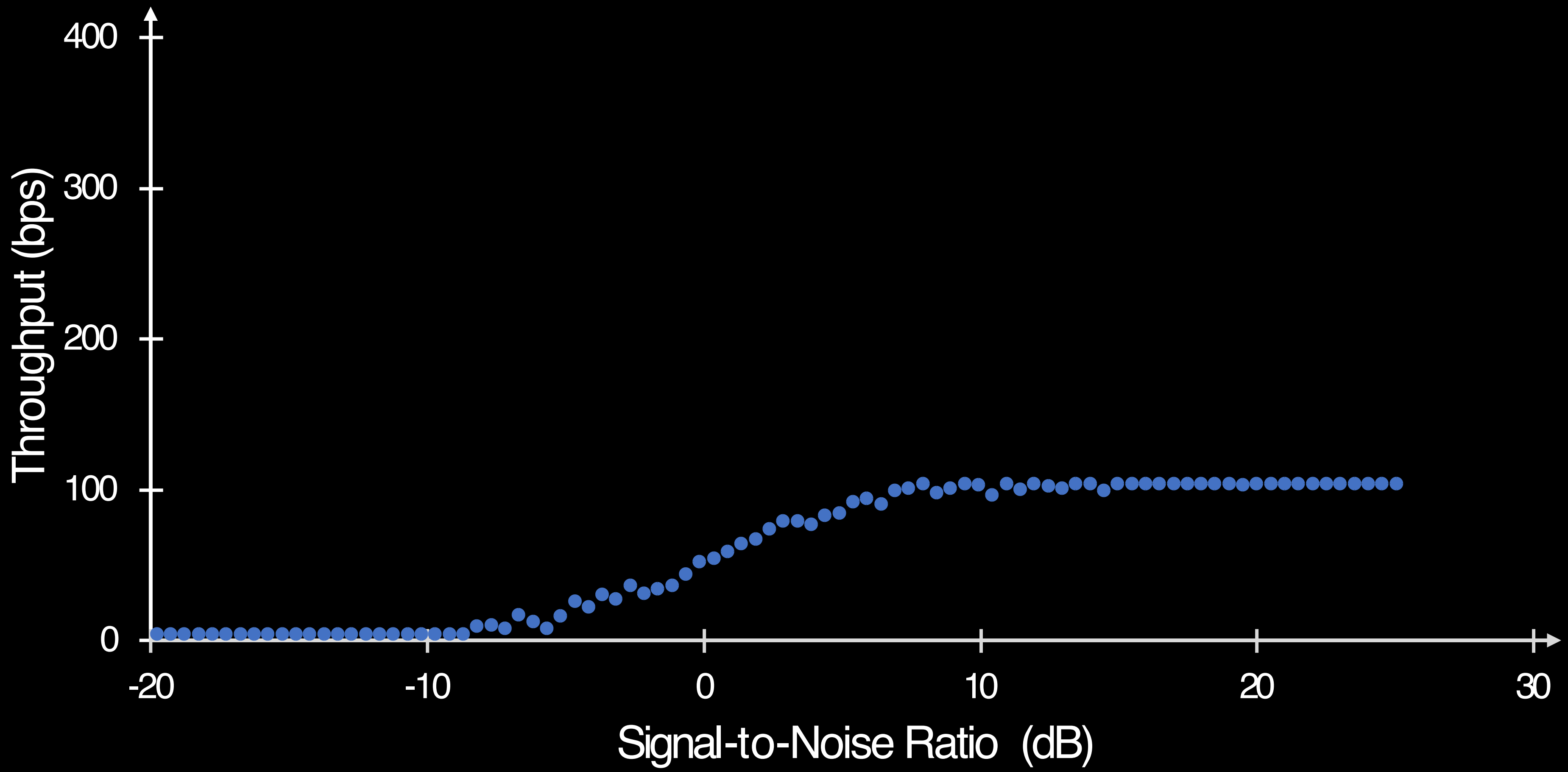

Throughput Results

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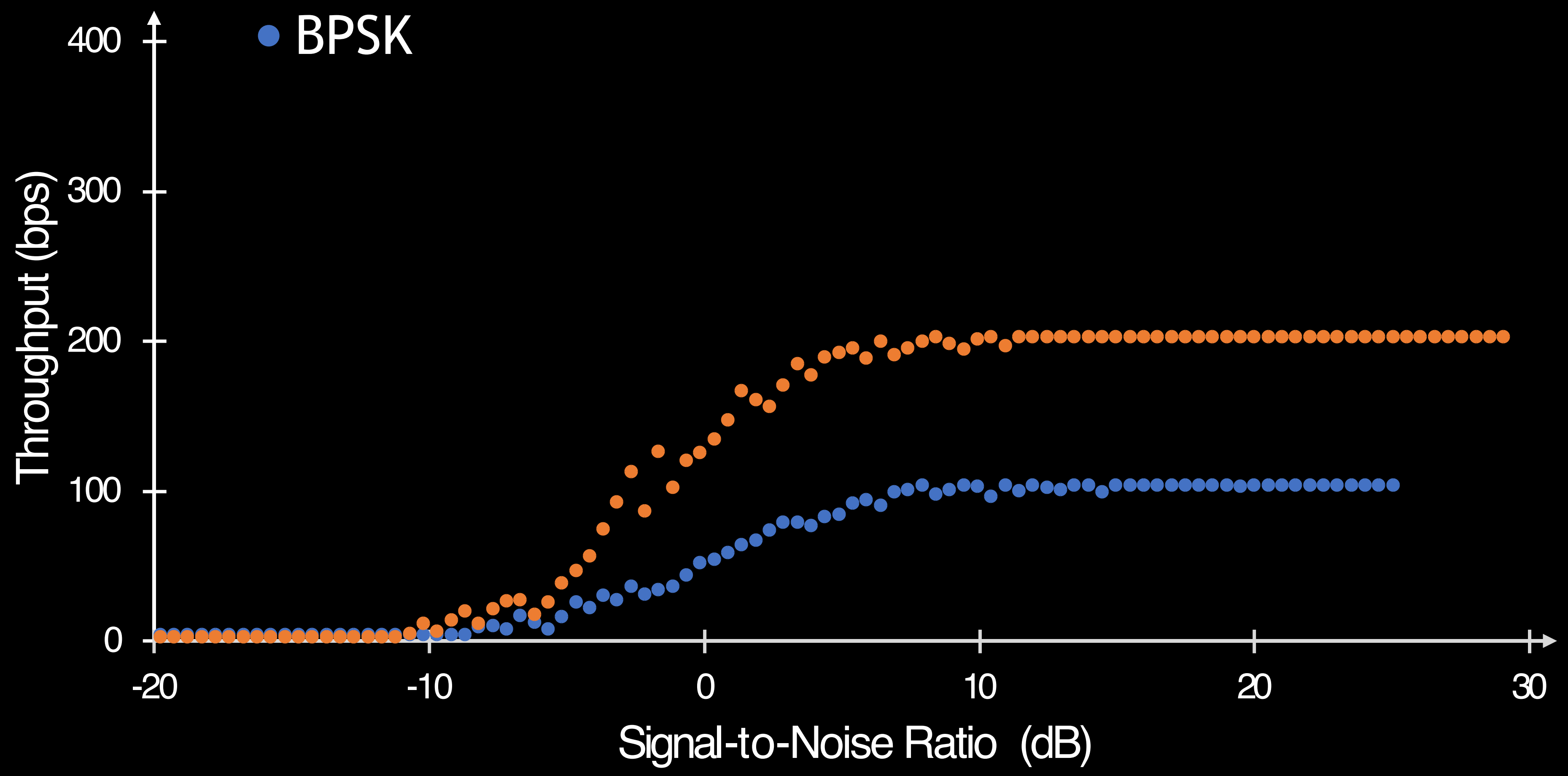
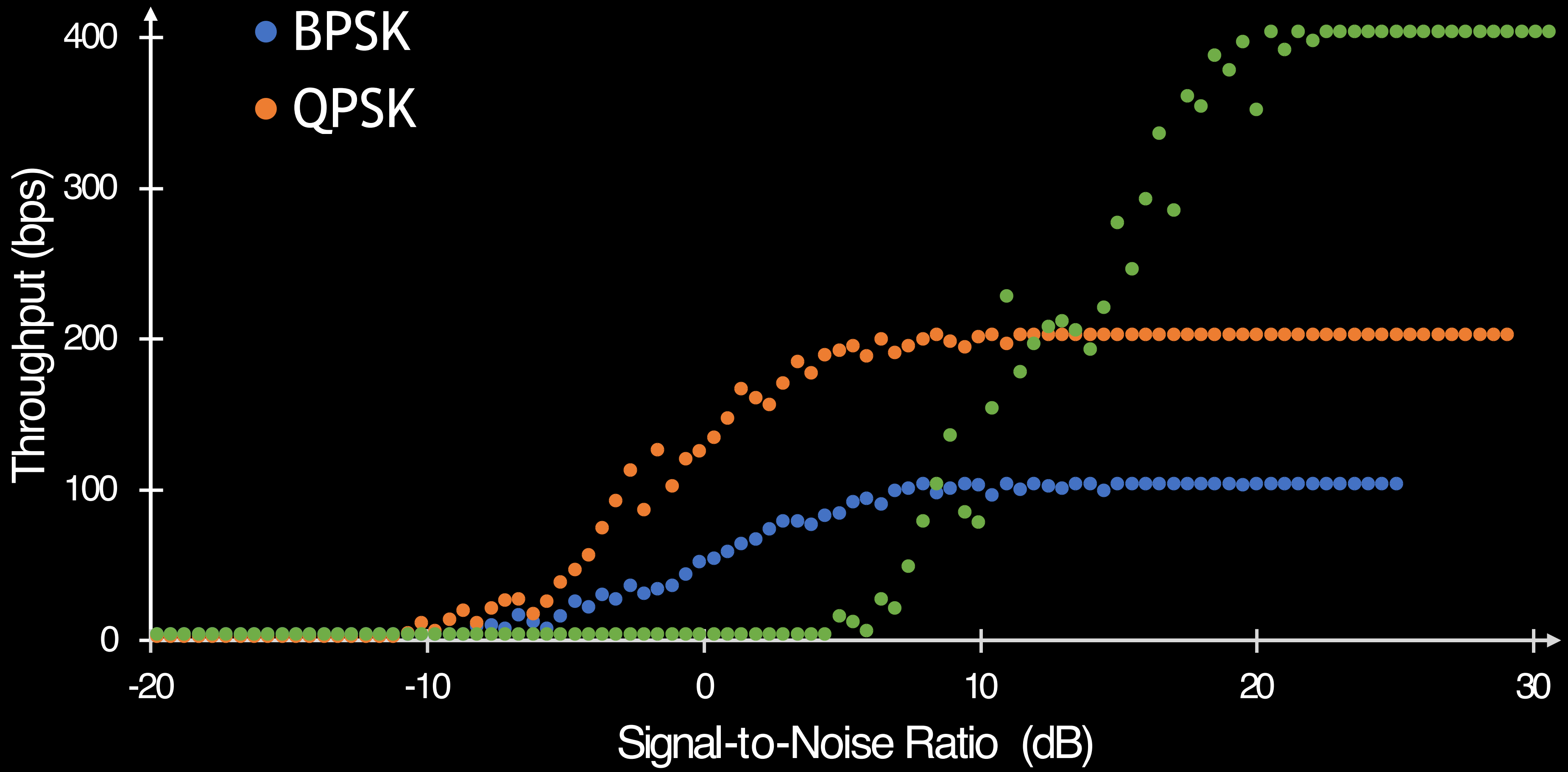


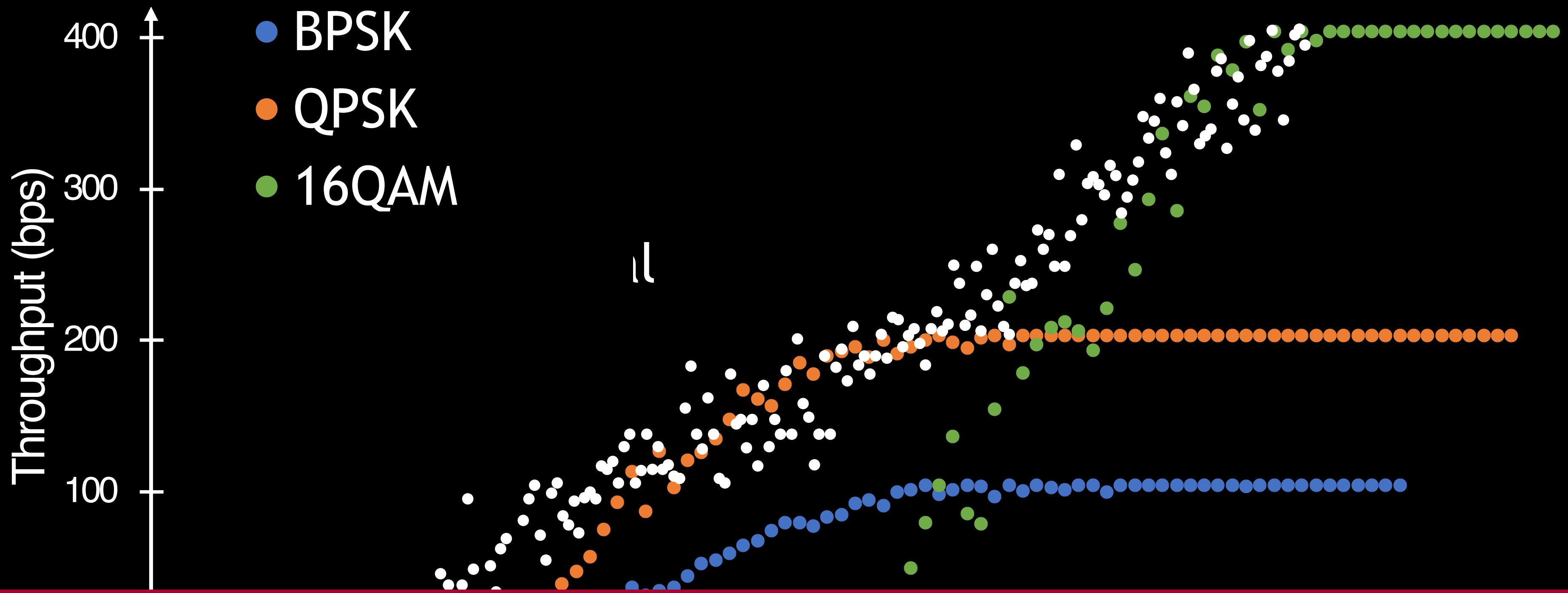
Throughput Results

<u>Experiment:</u> Vary the Power and Depth of Underwater Transmission



Throughput Results

<u>Experiment:</u> 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?

Next Class: 3D Reconstruction in NLOS

Required (Reviews)

- 3 papers, all of which are on new systems (2024/2025) on imaging with millimeter waves
- Taught by: Laura Dodds

Prep a 1-min pitch for your project idea