AmphiLight: Direct Air-Water Communication with Laser Light

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Waleed Akbar
MAS.S62: Ocean IoT

Slides source: https://www.usenix.org/sites/default/files/conference/protected-files/nsdi20_slides_carver.pdf

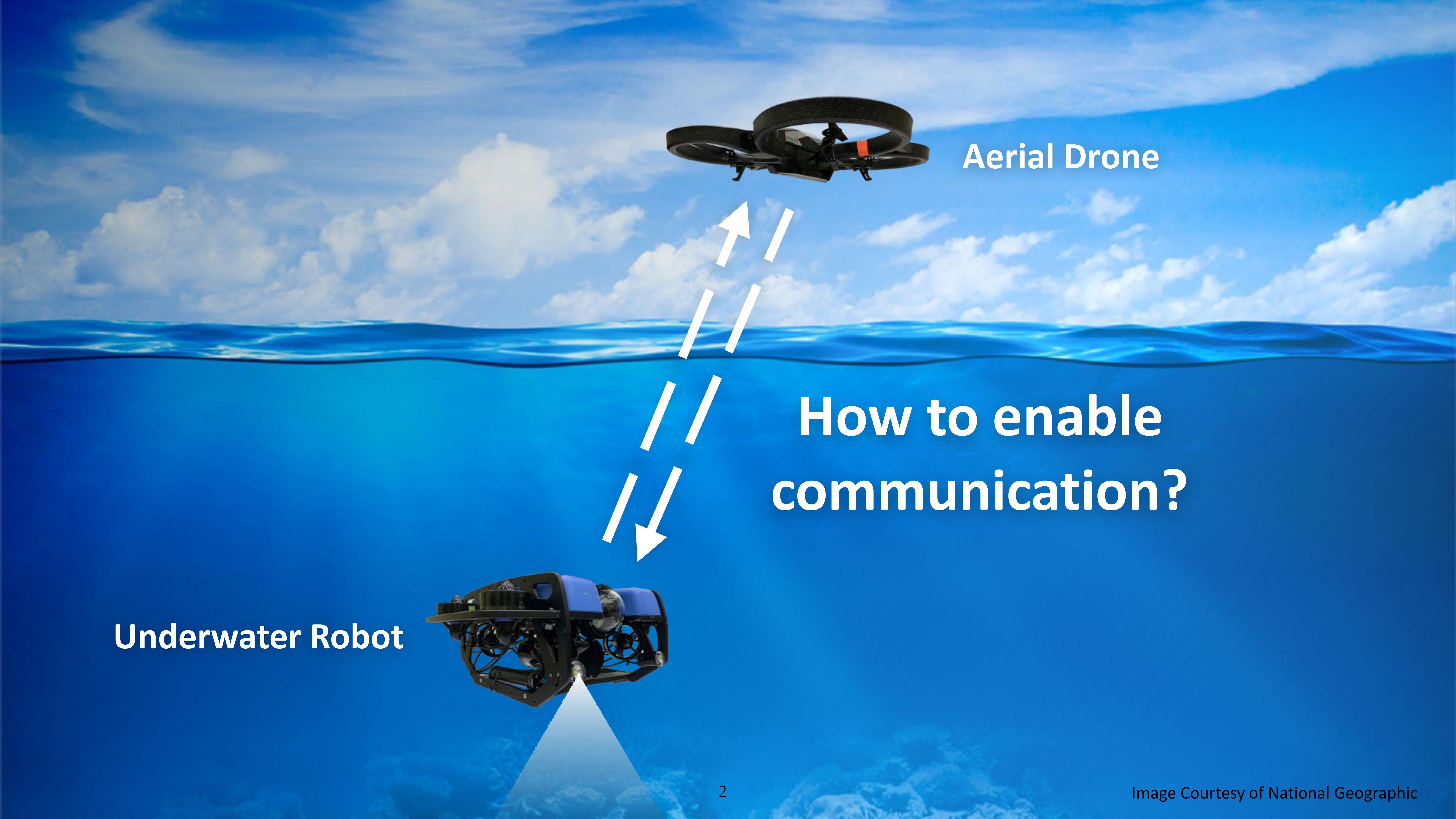


Image Courtesy of National Geographic

#1: Periodic Resurfacing

Aerial Drone

✗ Interrupts current task to transmit data

Underwater Robot

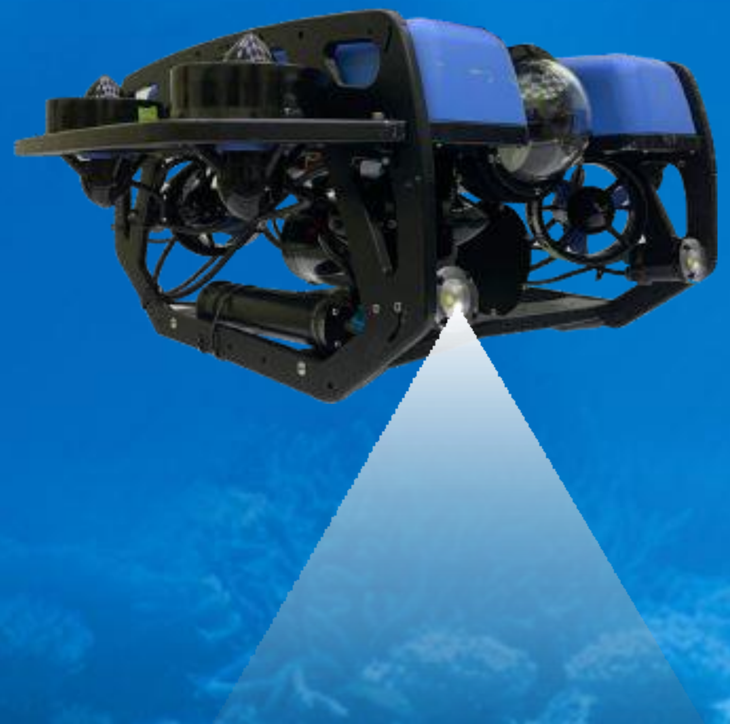


Image Courtesy of National Geographic

#2: Network of Buoys

✗Logistical and deployment overhead

Image Courtesy of National Geographic

Need a direct air-water communication link!

Image Courtesy of National Geographic

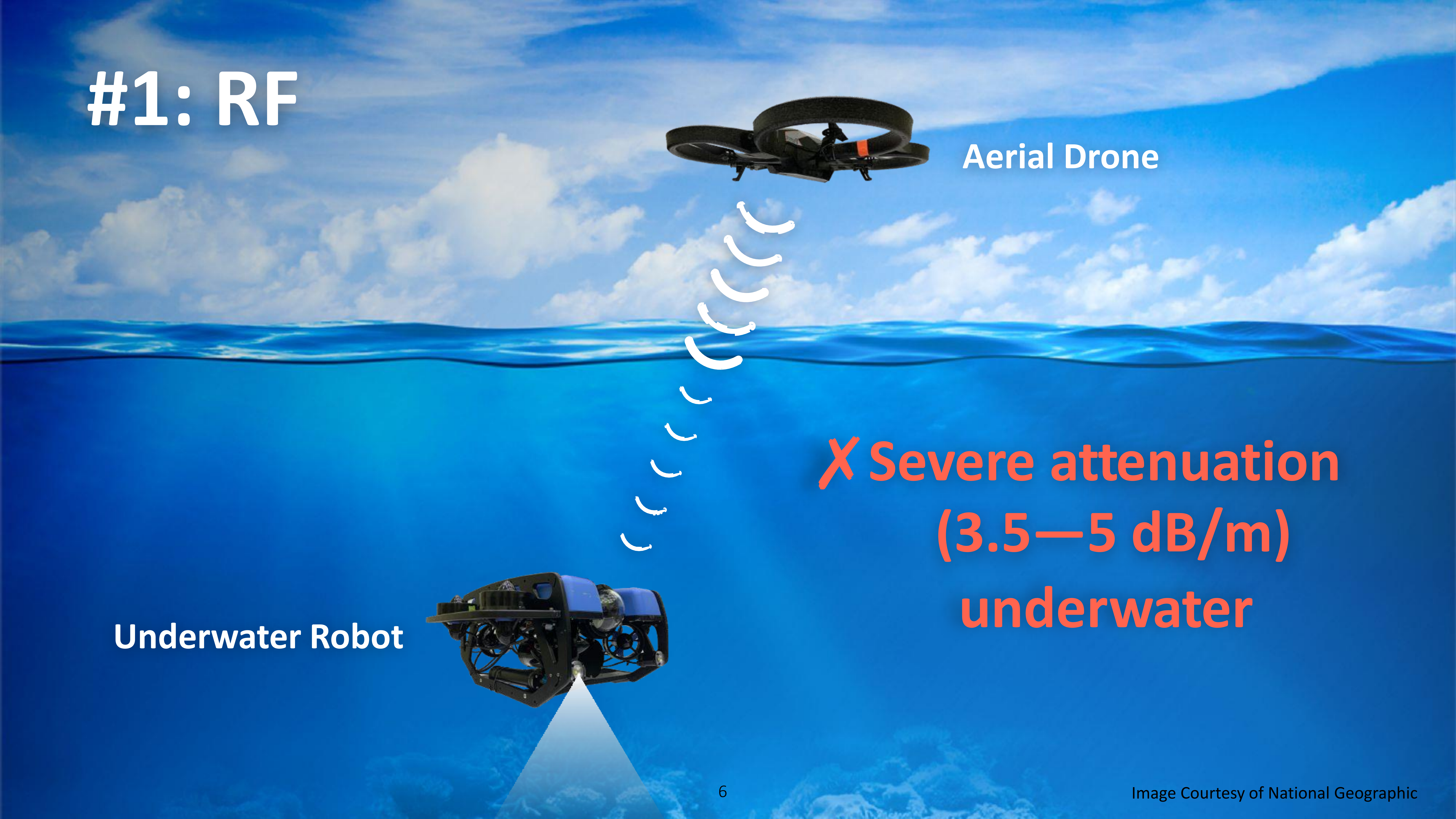
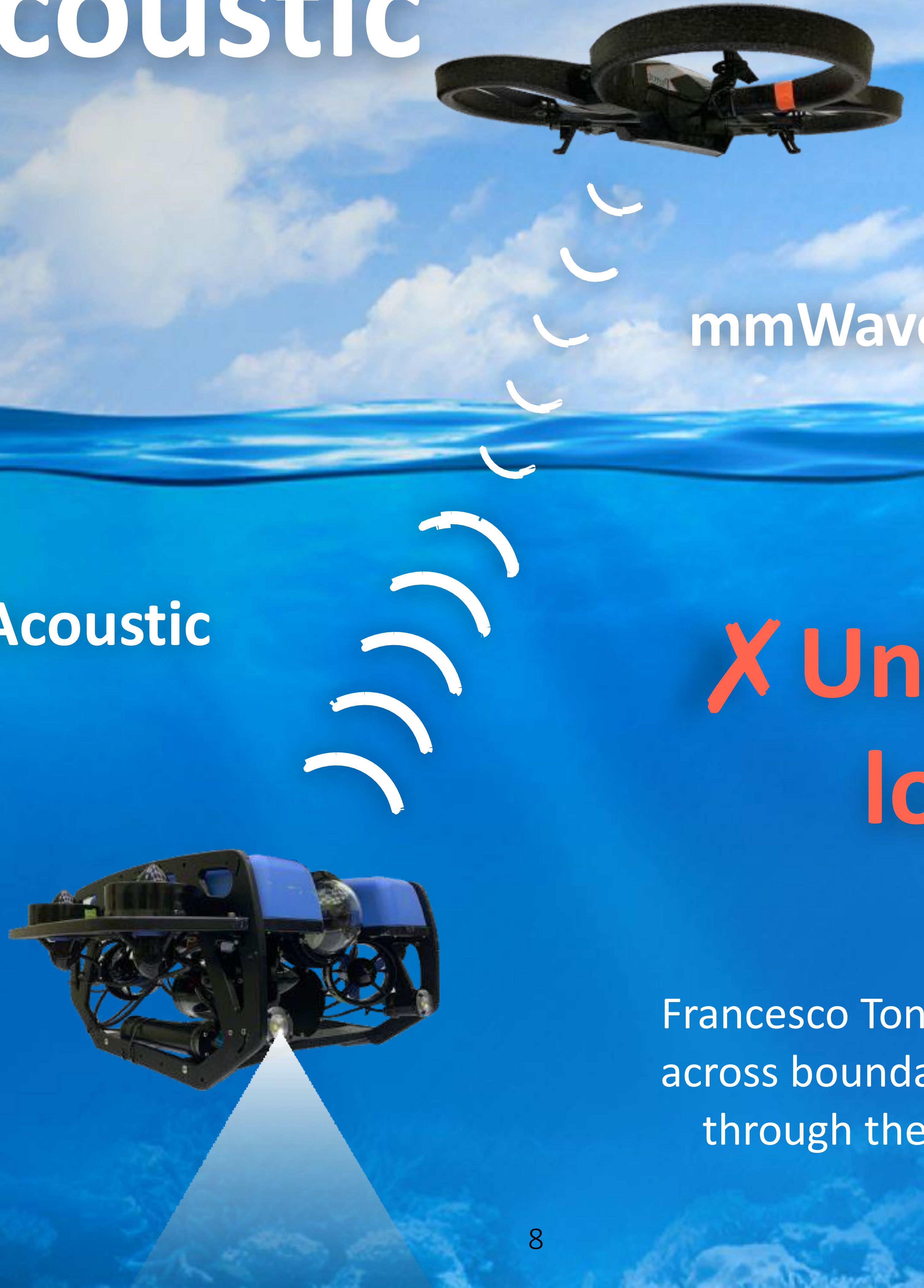

#1: RF
Aerial Drone
✗ Severe attenuation
(3.5—5 dB/m)
underwater
Underwater Robot
Image Courtesy of National Geographic

Image Courtesy of National Geographic

#3: RF + Acoustic



✗ Unidirectional and low throughput

Francesco Tonolini and Fadel Adib. 2018. Networking across boundaries: enabling wireless communication through the water-air interface. (SIGCOMM ’18).

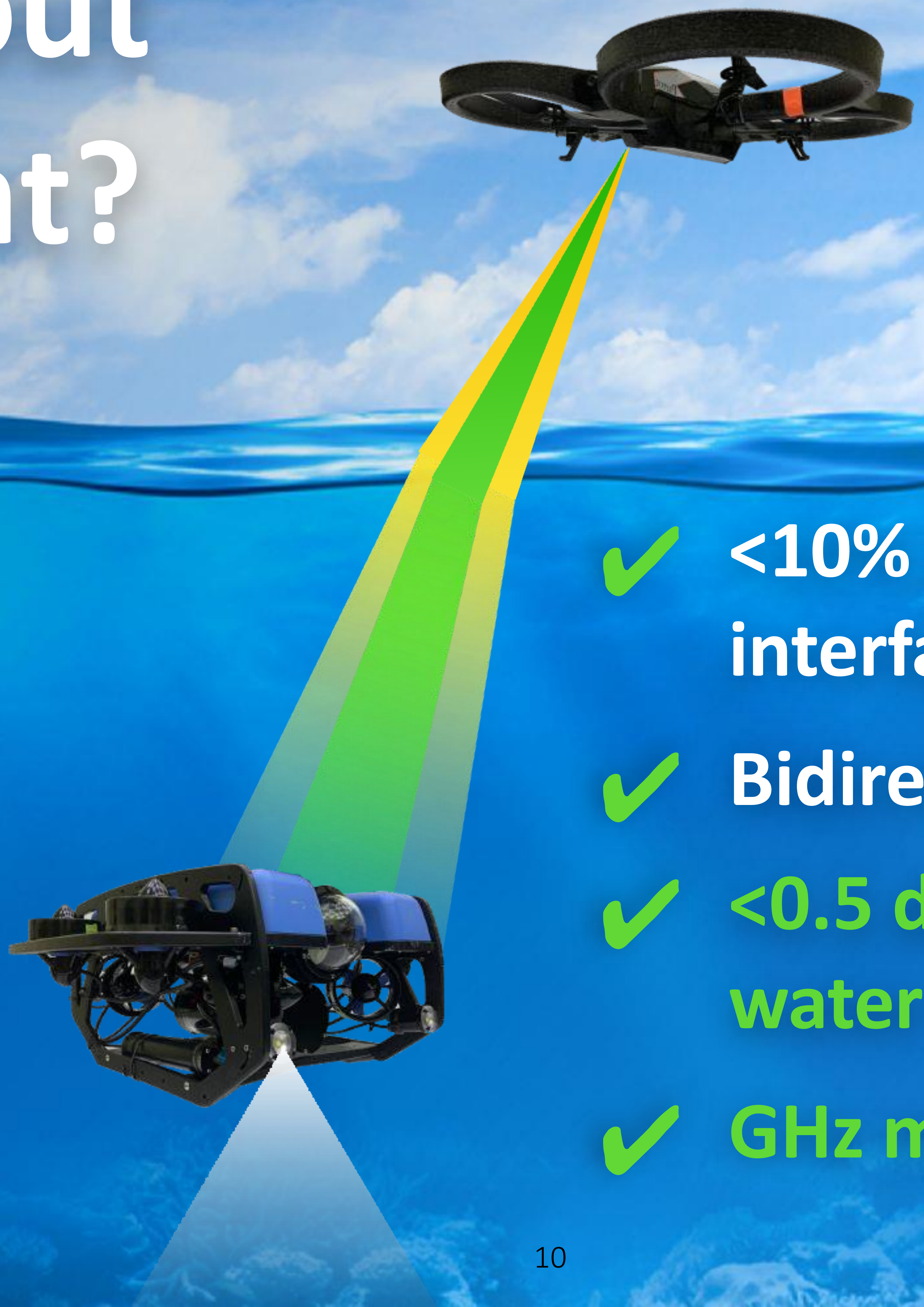
What about Light?

Aerial Drone

Underwater Robot

- ✔ <10% power loss through interface
- ✔ Bidirectional

What about Laser Light?

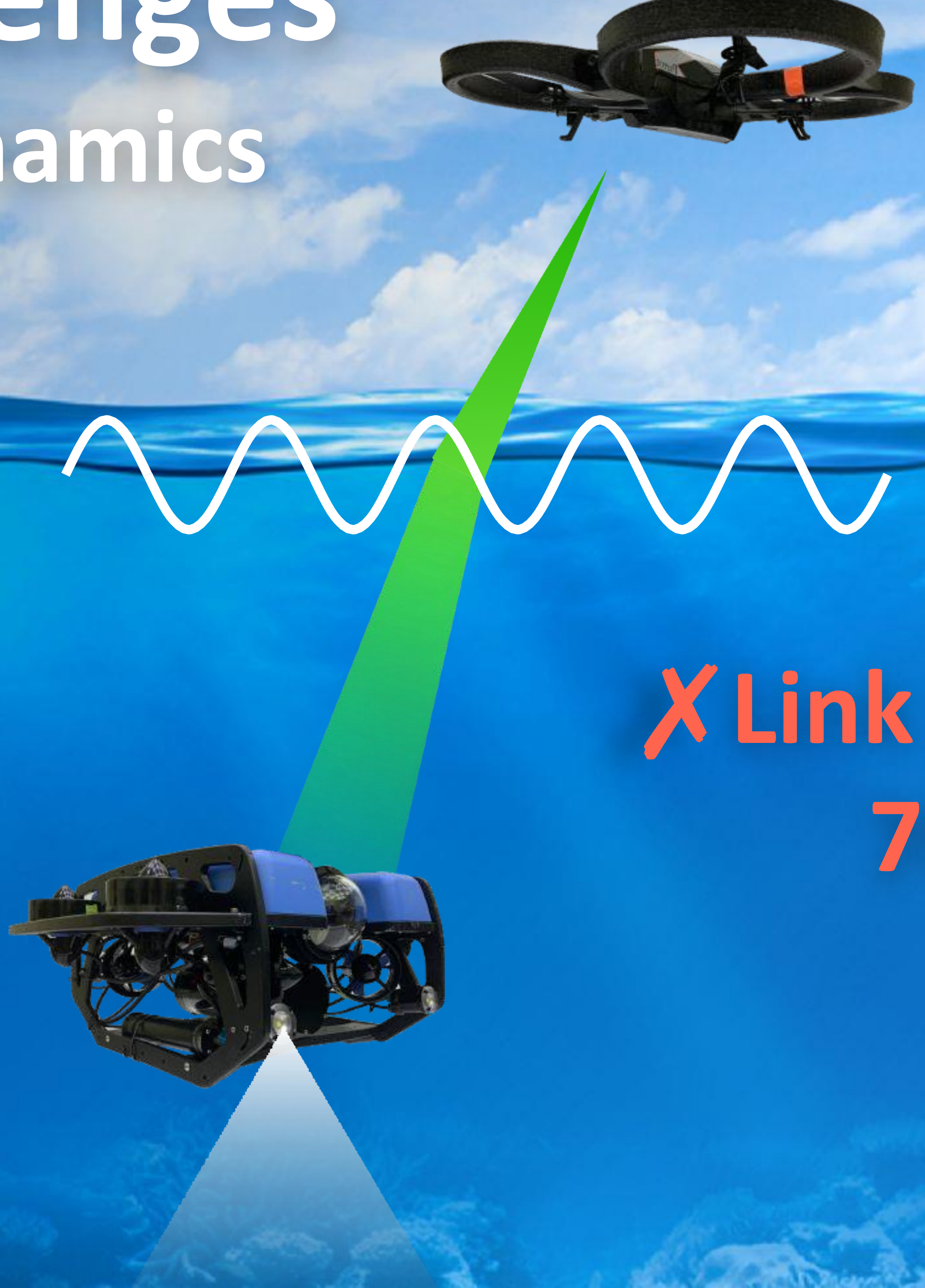


- ✔ <10% power loss through interface
- ✔ Bidirectional
- ✔ <0.5 db/m attenuation in water (at 420 nm – 550 nm)
- ✔ GHz modulation

Image Courtesy of National Geographic

Key Challenges

#1: Wave dynamics



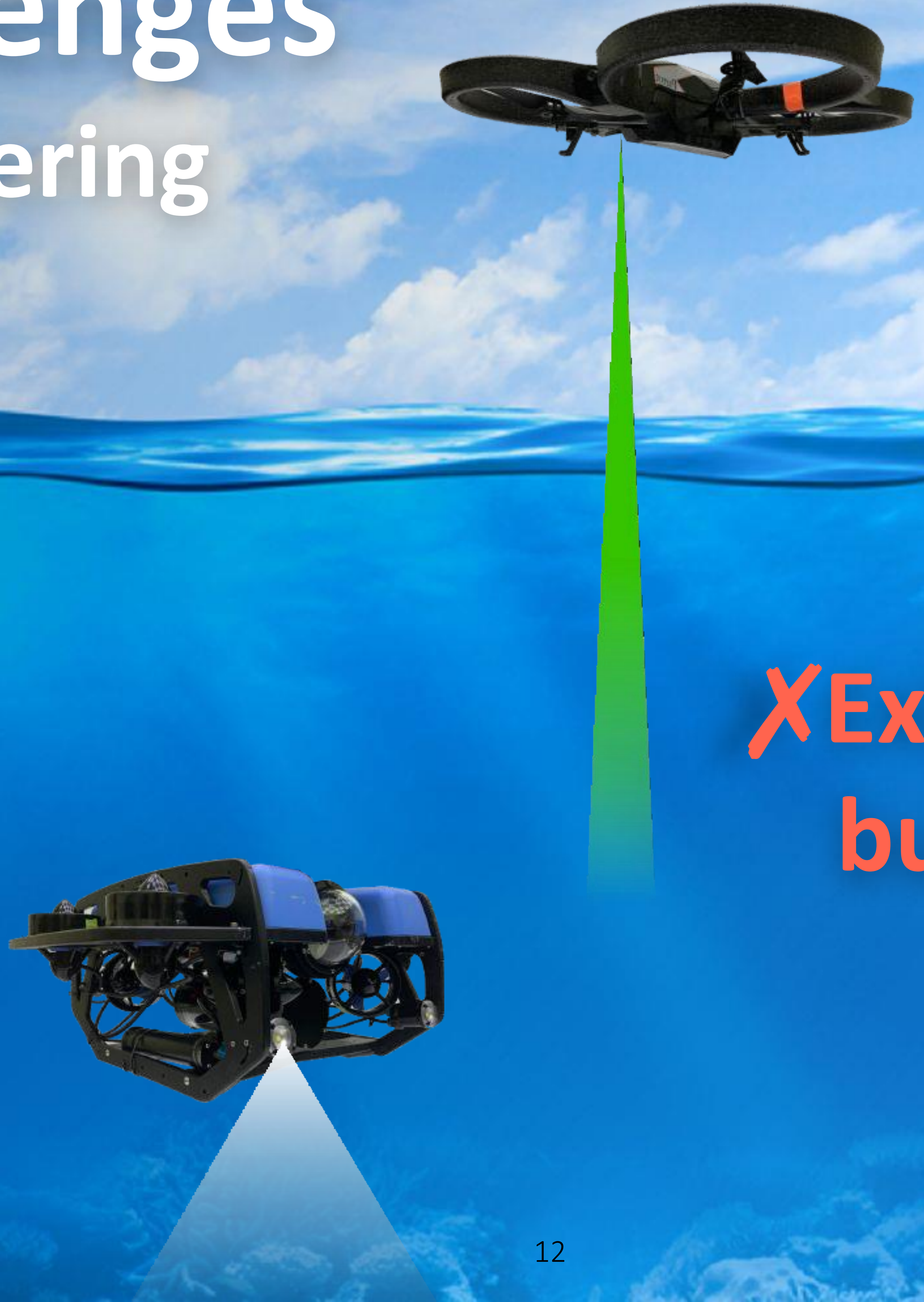
✗ Link unavailable up to 70% of the time

Image Courtesy of National Geographic

Key Challenges

#2: Beam steering

Aerial Drone



Underwater Robot

✗Existing methods are bulky and expensive

Image Courtesy of National Geographic, SEFREA

Key Challenges

#3: Ambient light

Sun

Aerial Drone

≈ 100,000 LX

✗ Sensor saturation

Underwater Robot

Image Courtesy of National Geographic

AmphiLight

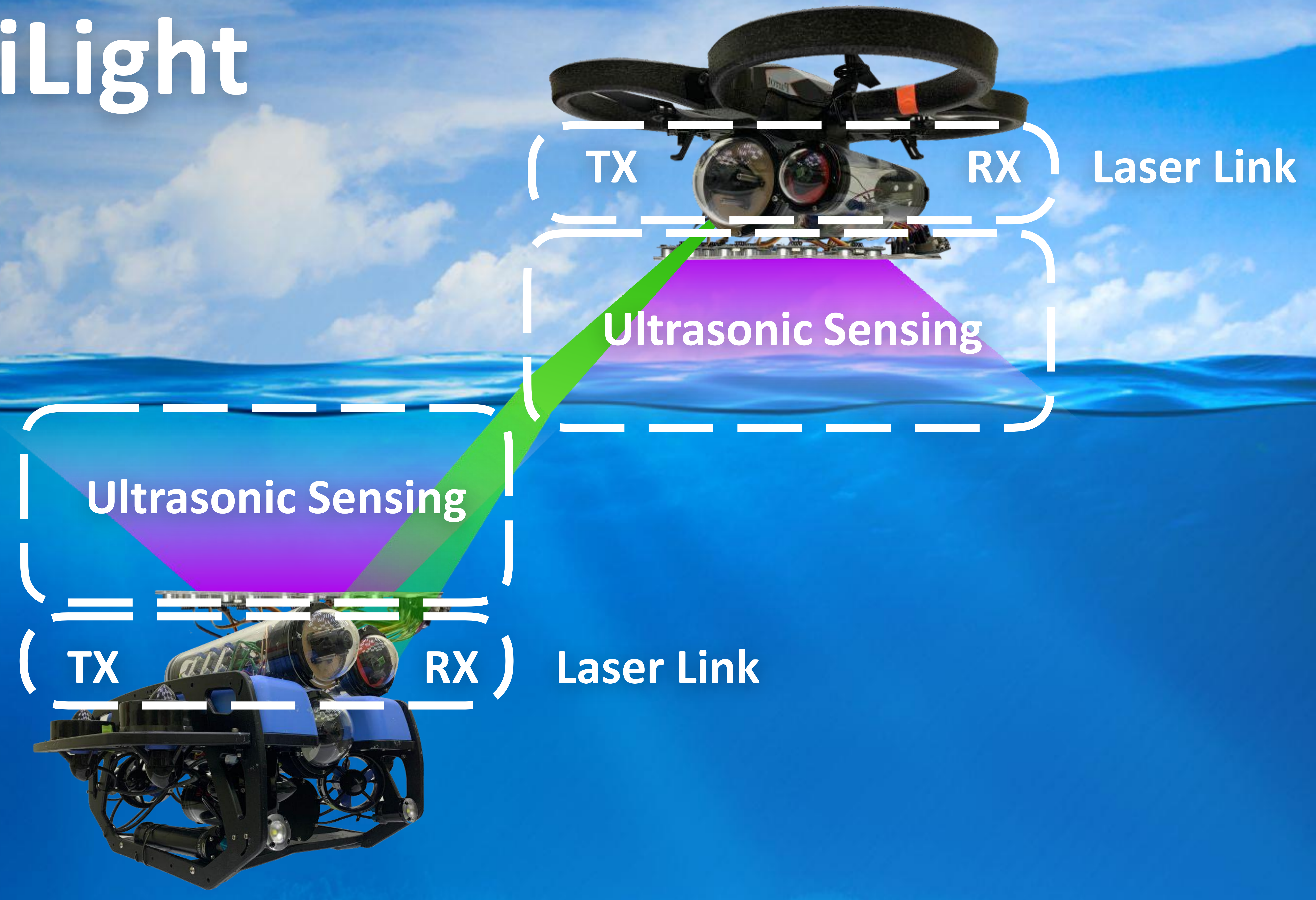
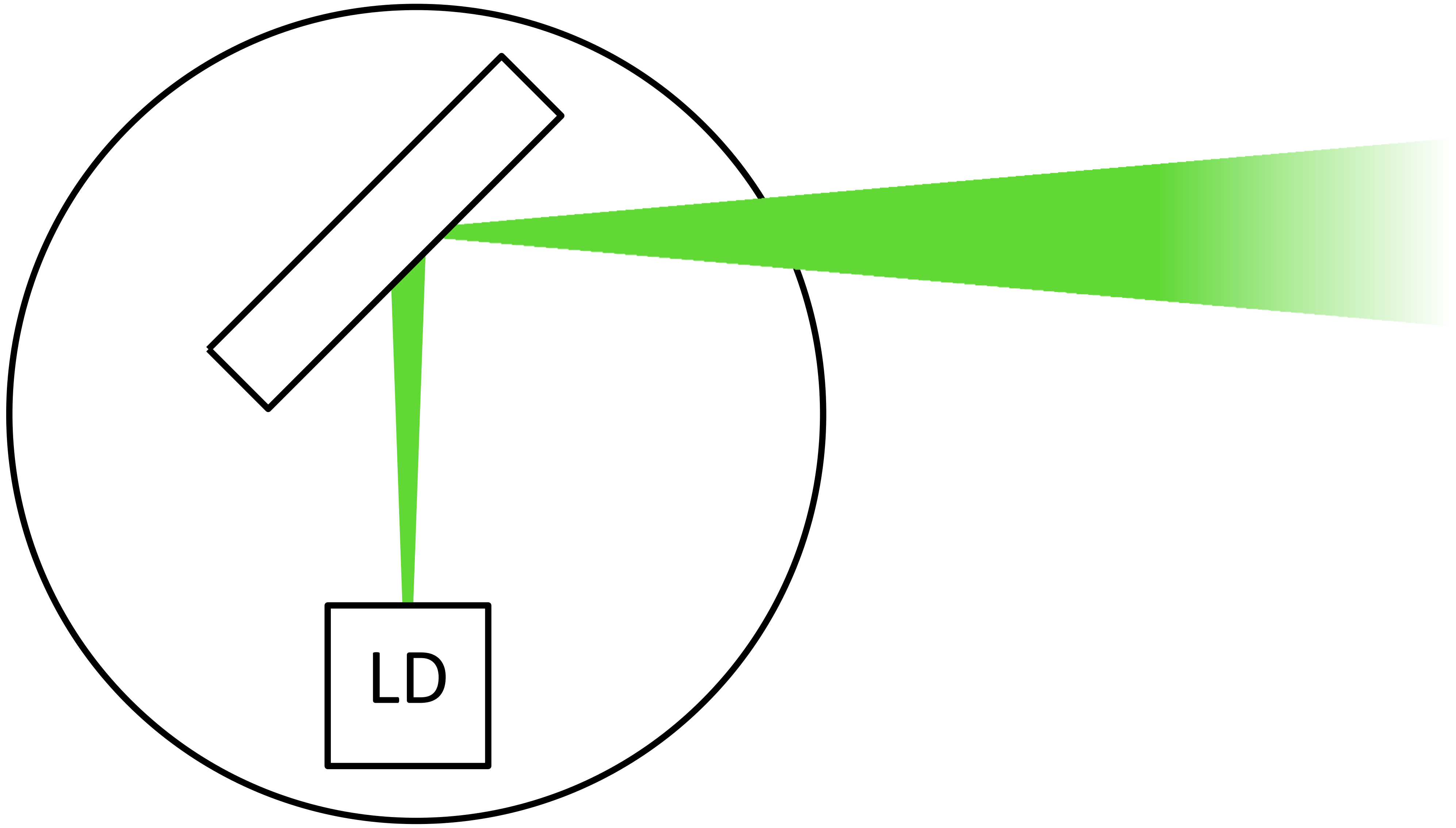


Image Courtesy of National Geographic

Transmitter Design

Beam Steering

- ☐ Full-hemisphere
- ☐ Fine-grained
- ☐ Portable



Transmitter Design

Beam Steering

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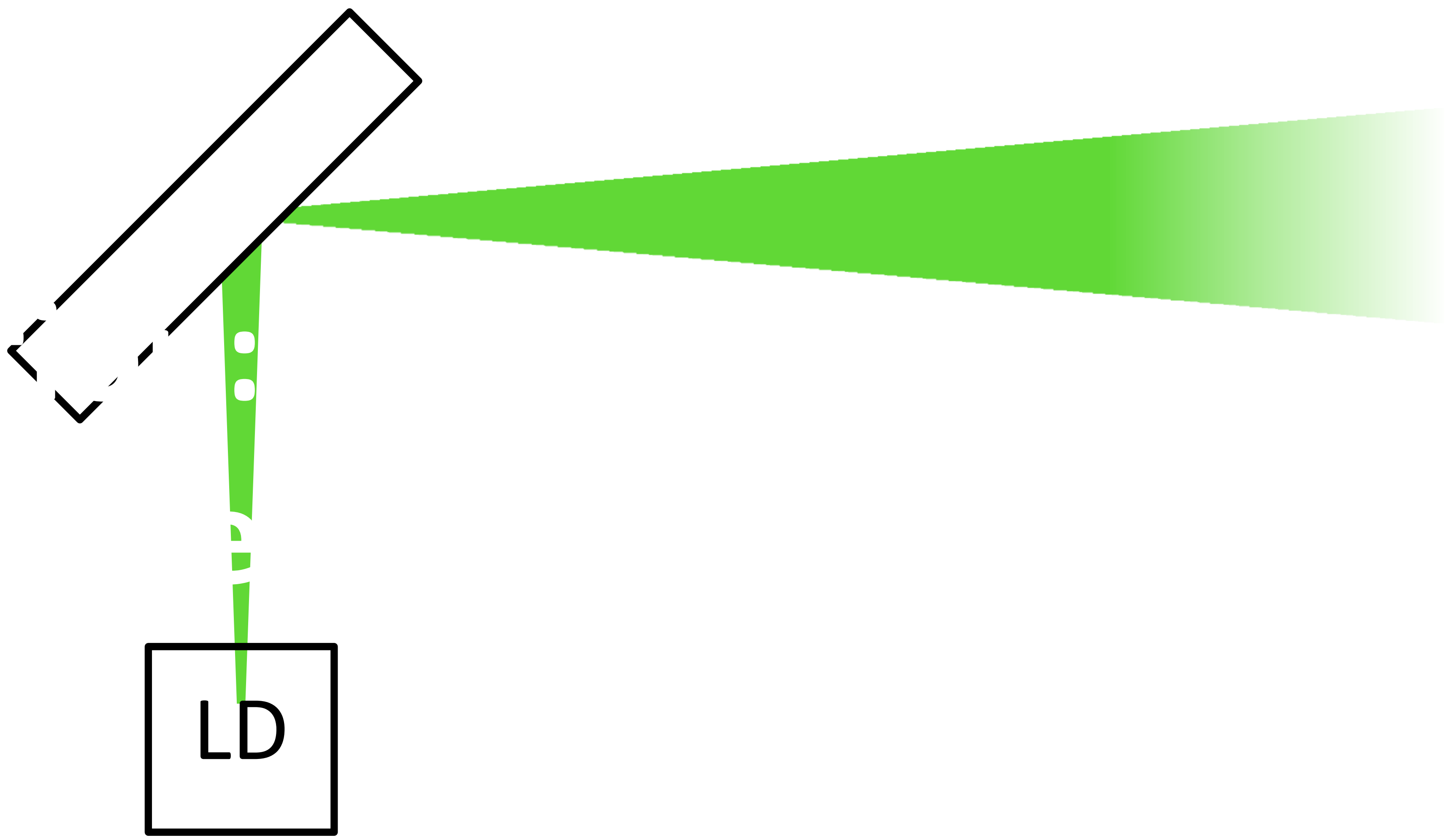
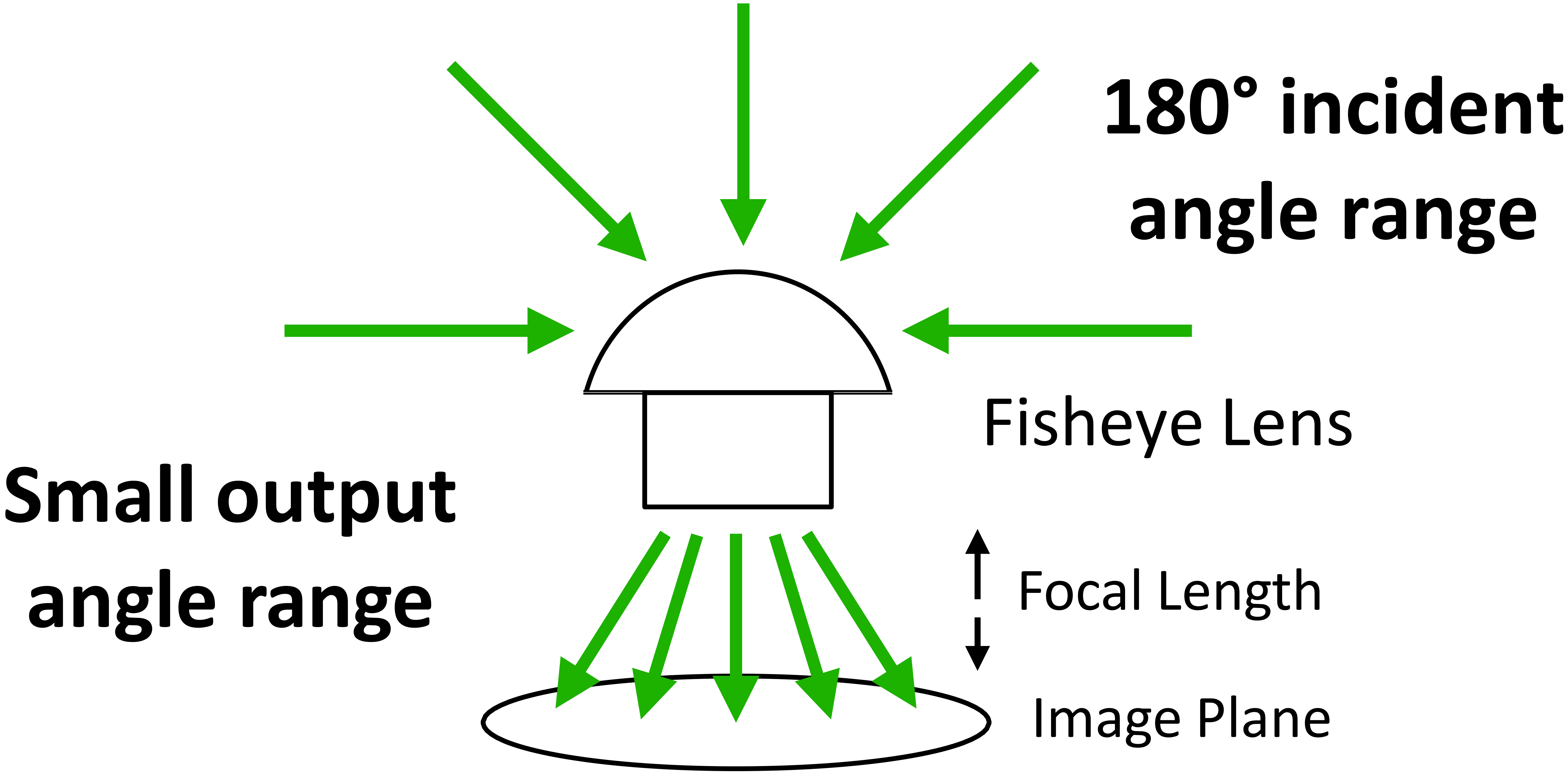


MEMS Mirror

TX Design: Full-Hemisphere Beam Steering

Exploit fisheye lens to expand MEMS mirror steering range



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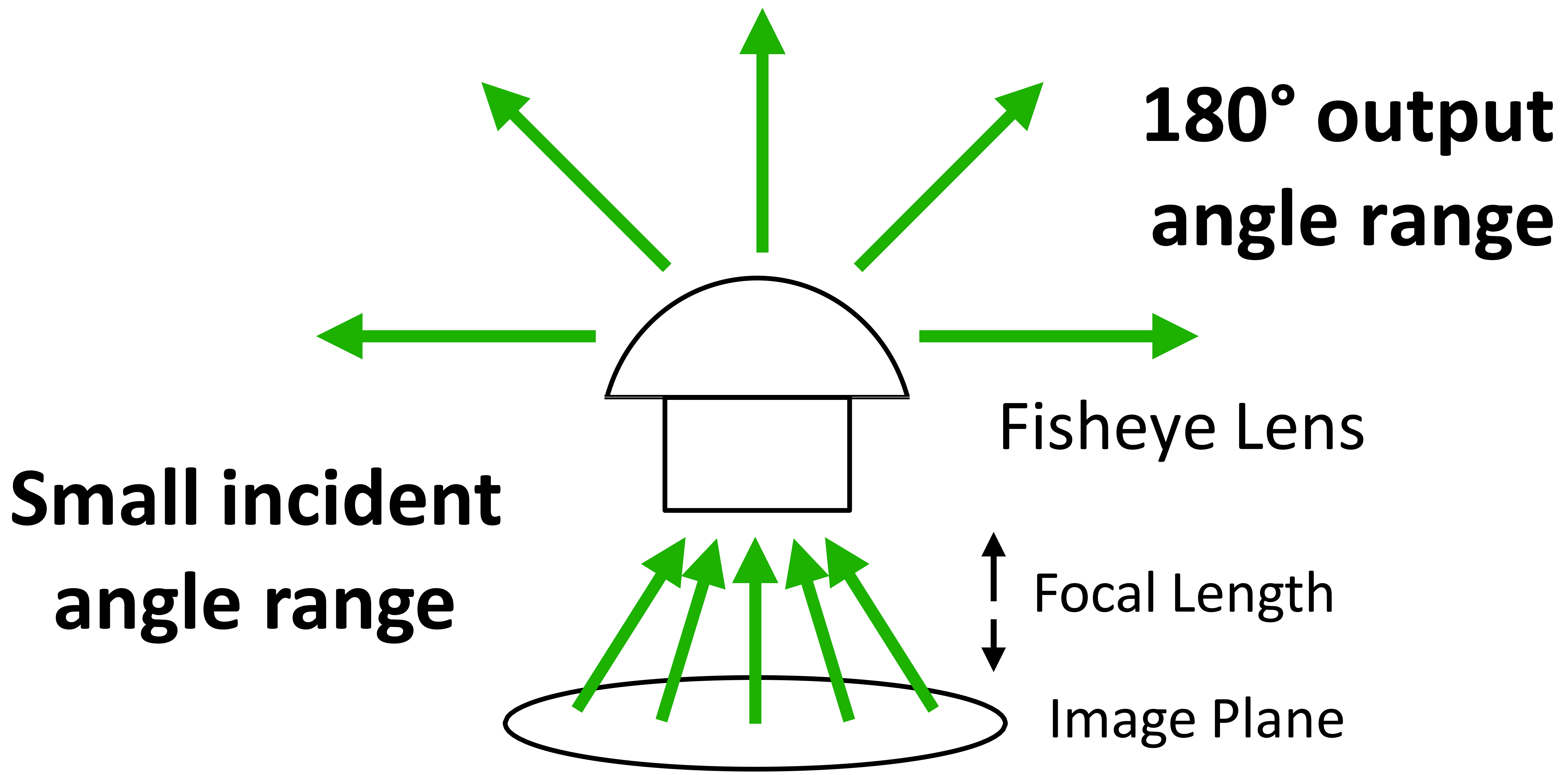

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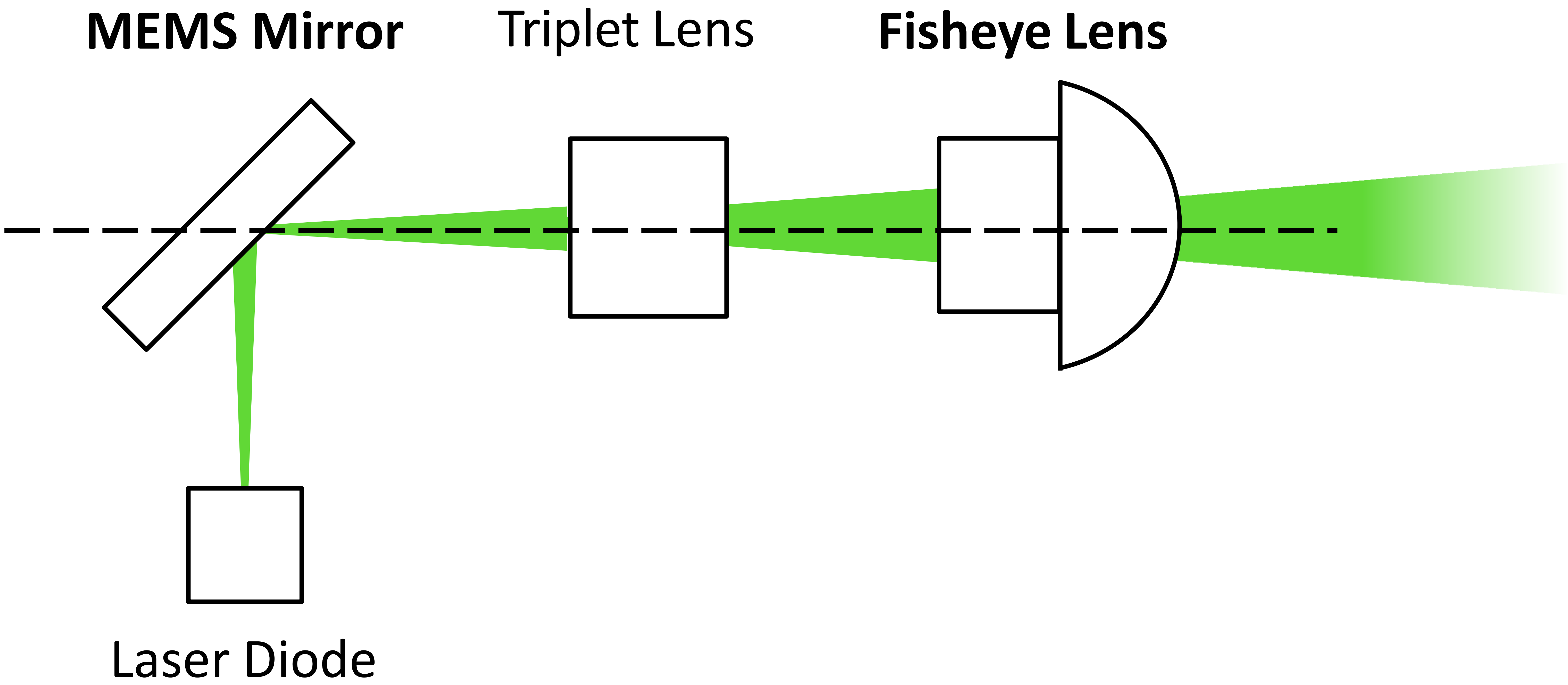

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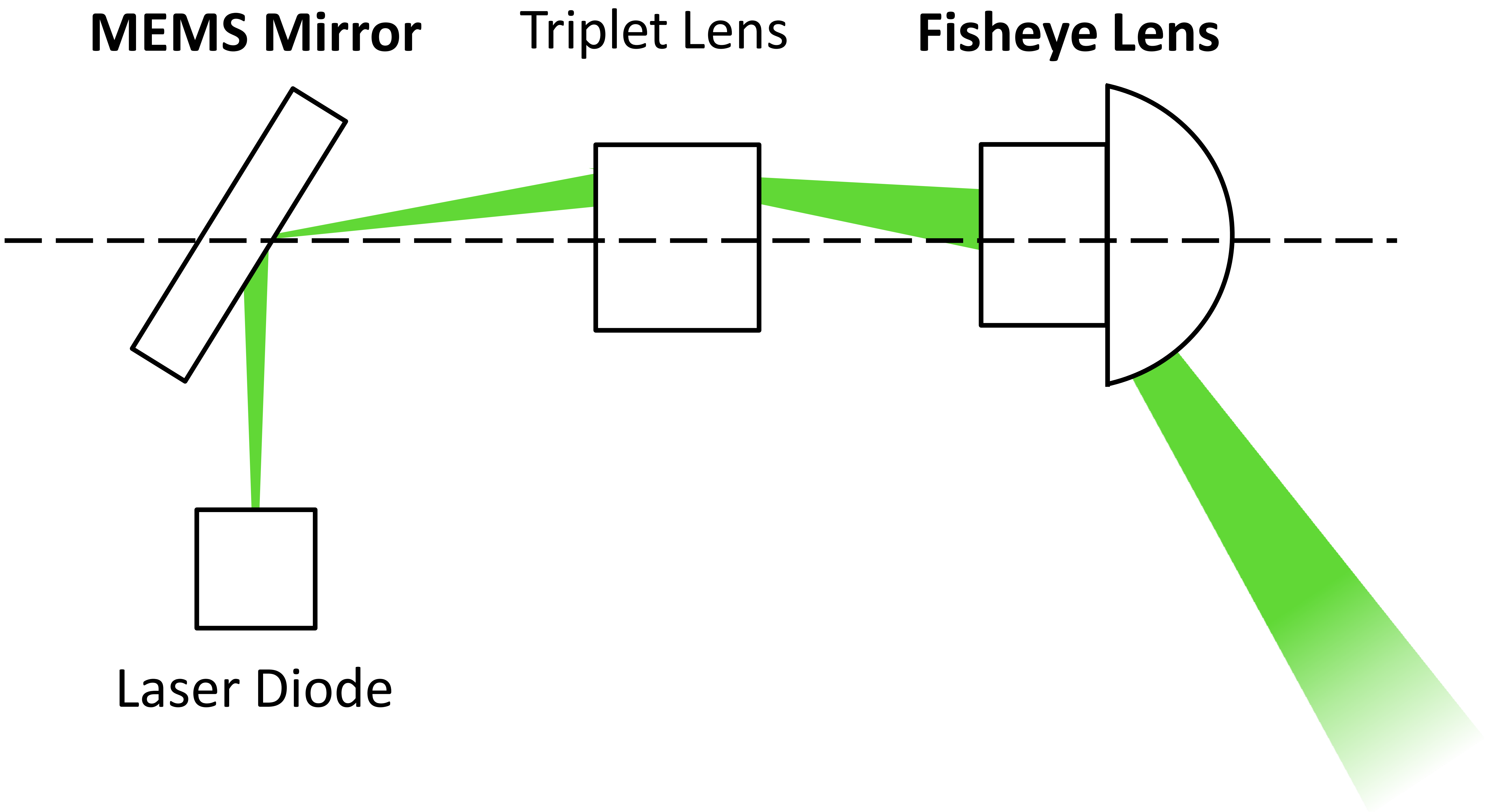

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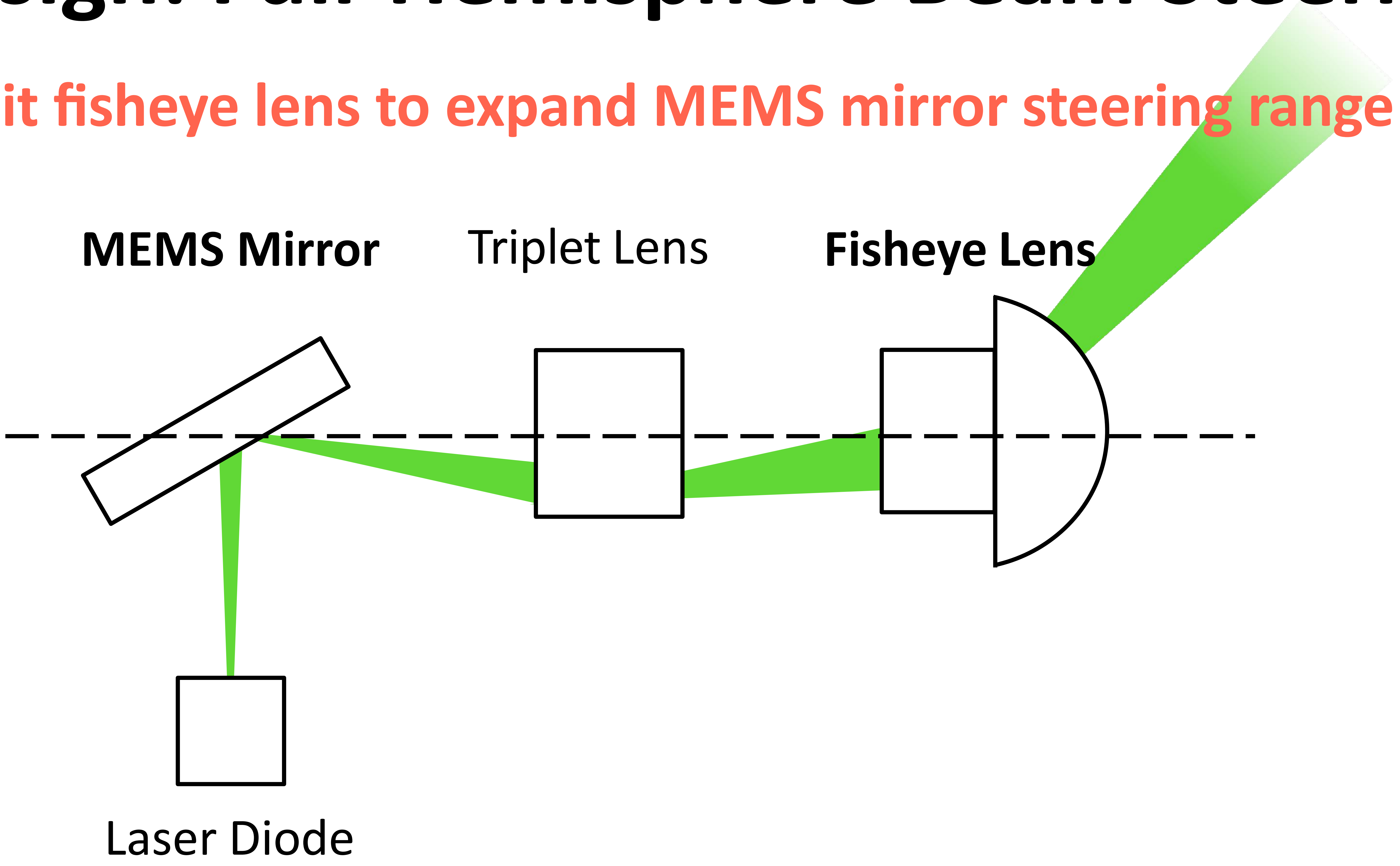

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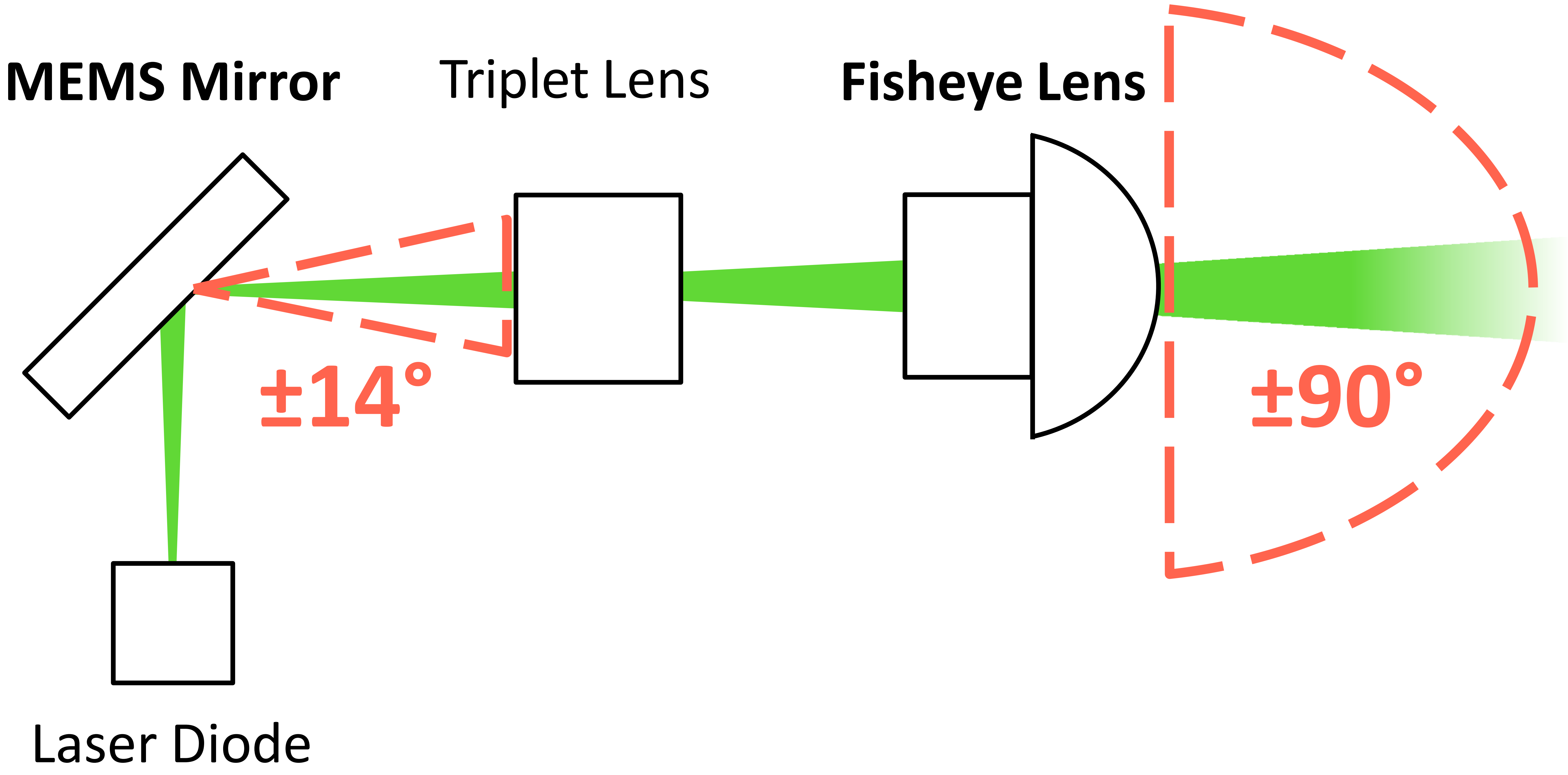


Receiver Design

- Need to extract laser light in strong ambient light condiMons

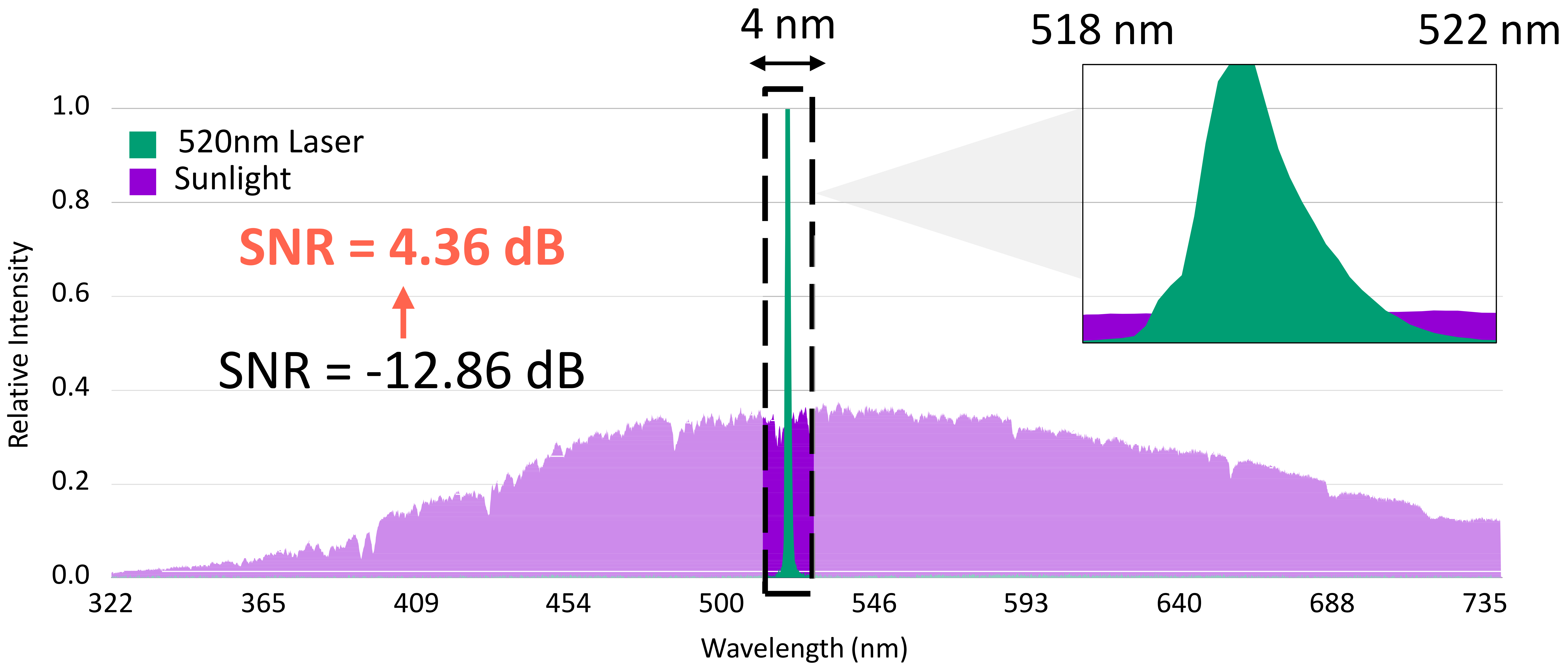


Image Courtesy of Thorlabs

AmphiLight

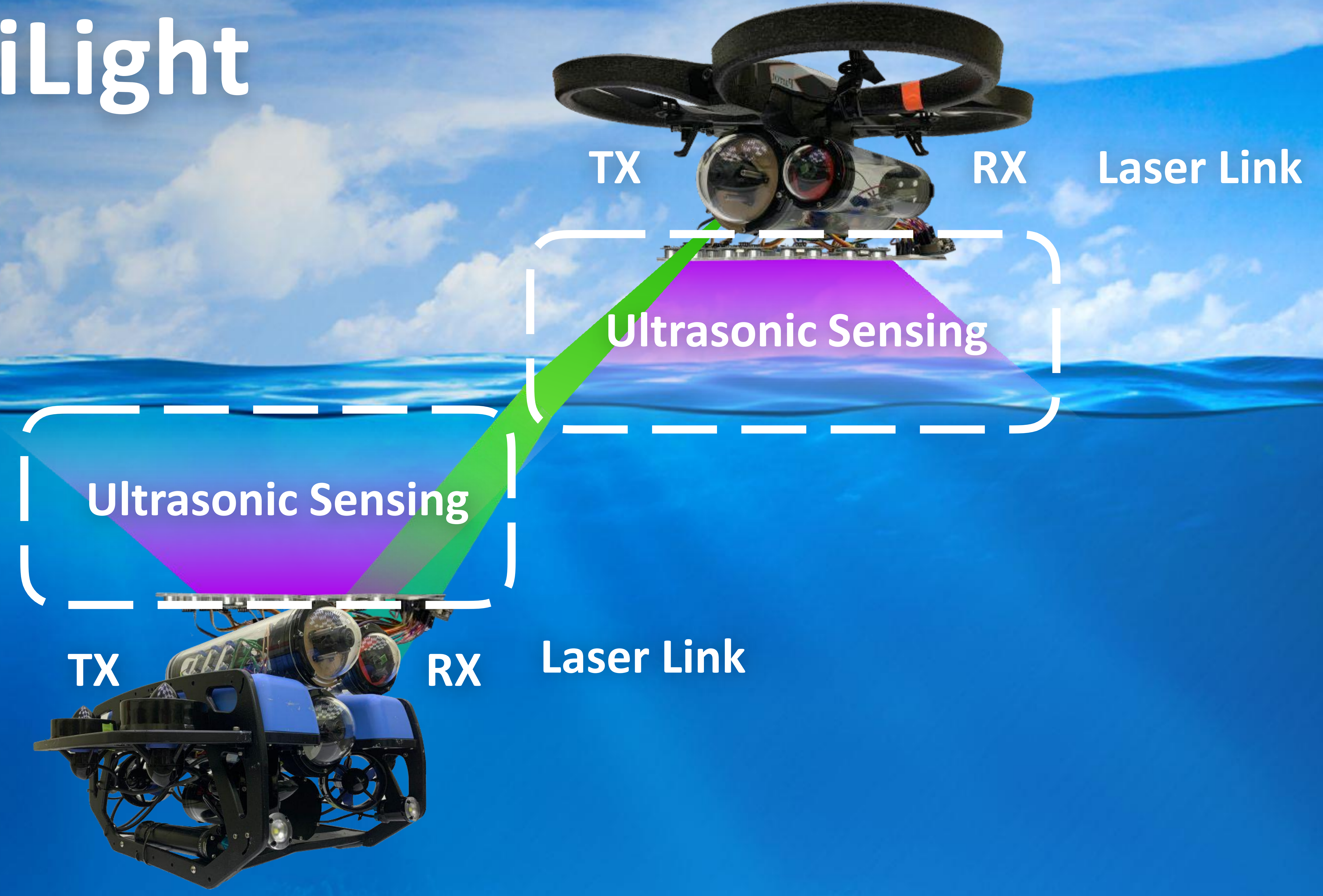
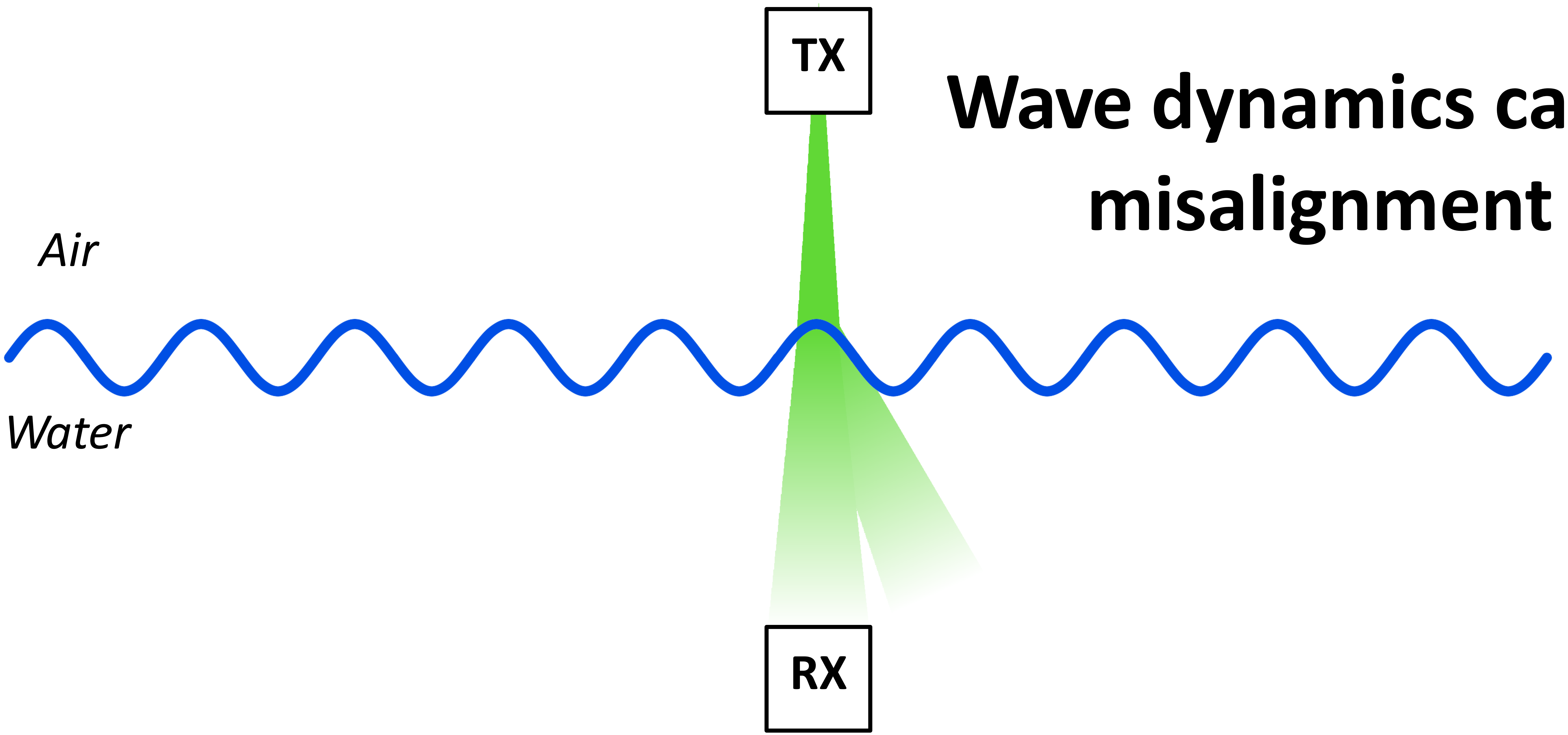


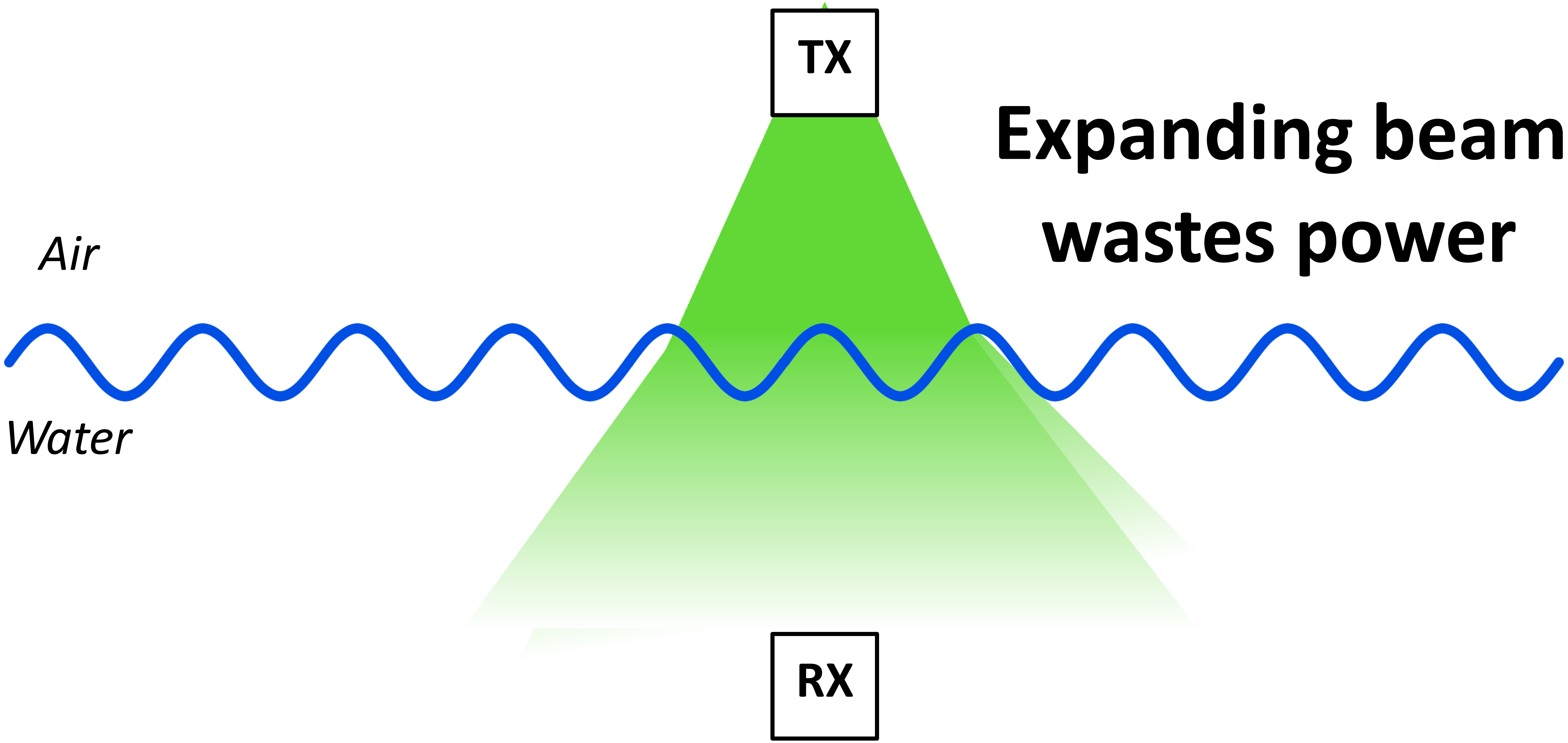
Image Courtesy of National Geographic

Design: Dealing with Wave Dynamics



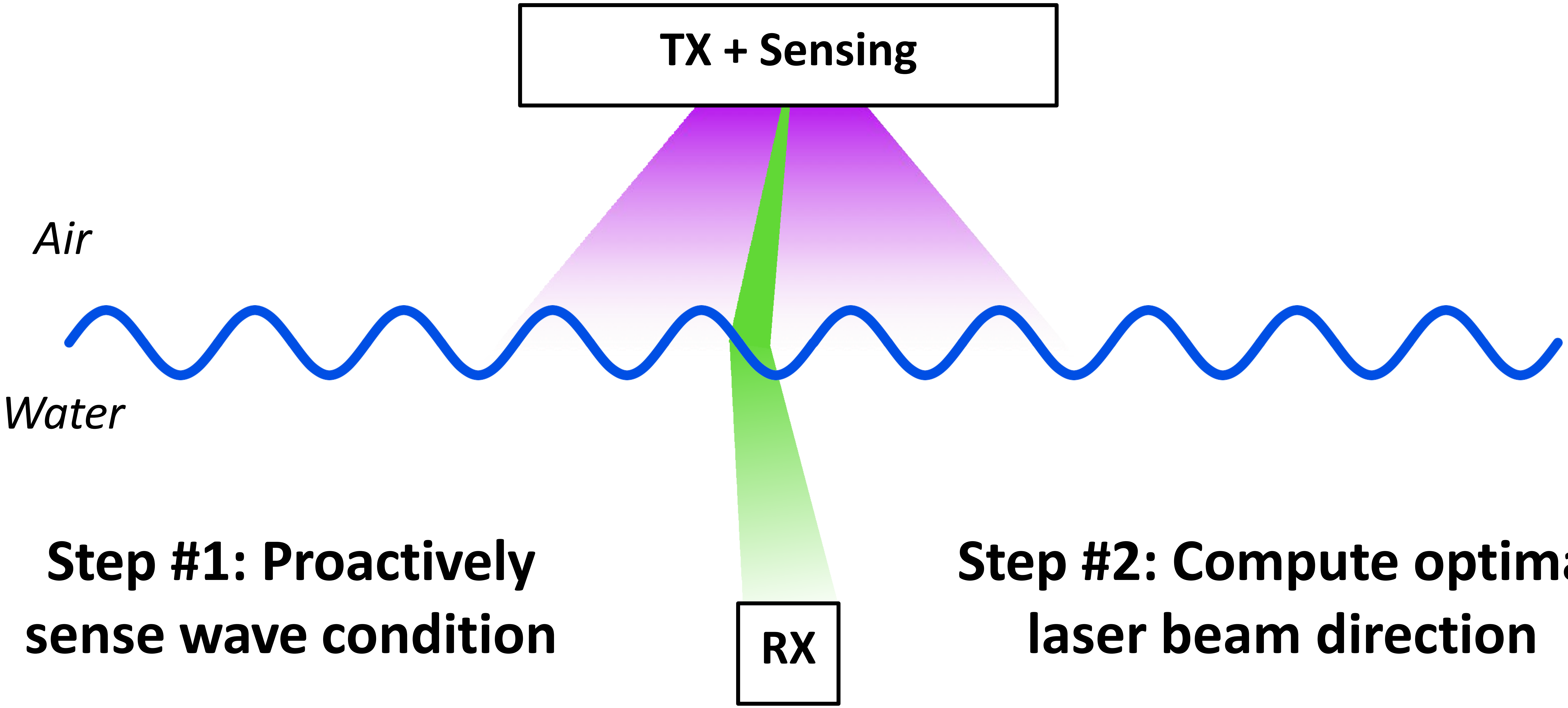
Wave dynamics cause misalignment

Design: Dealing with Wave Dynamics



Expanding beam wastes power

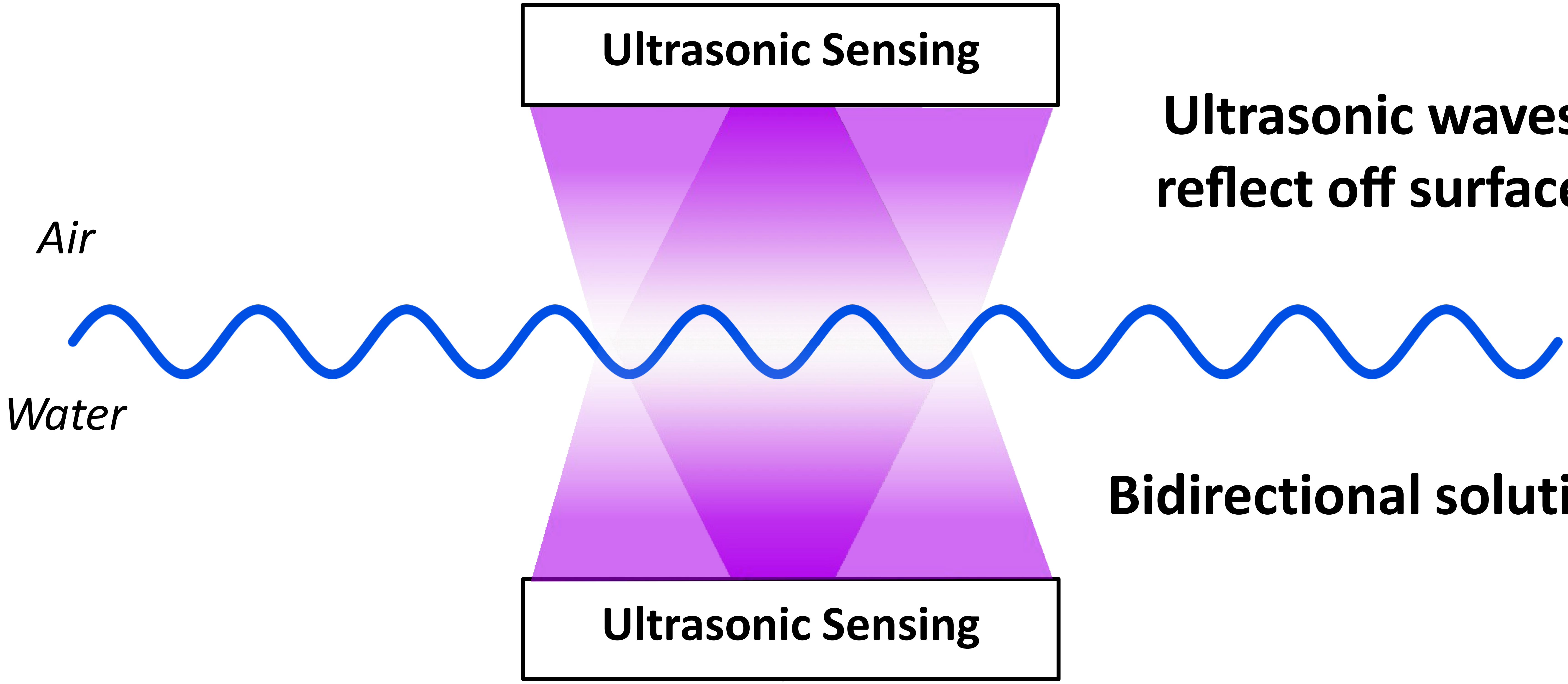
Design: Dealing with Wave Dynamics



Step #1: Proactively sense wave condition

Step #2: Compute optimal laser beam direction

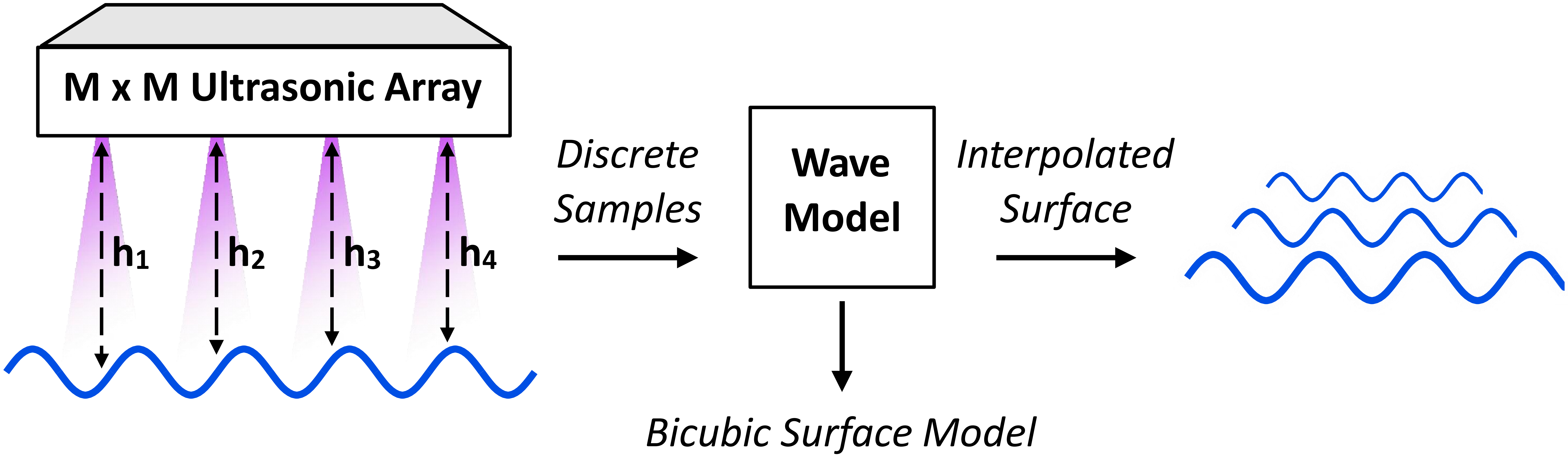
Design: Dealing with Wave Dynamics



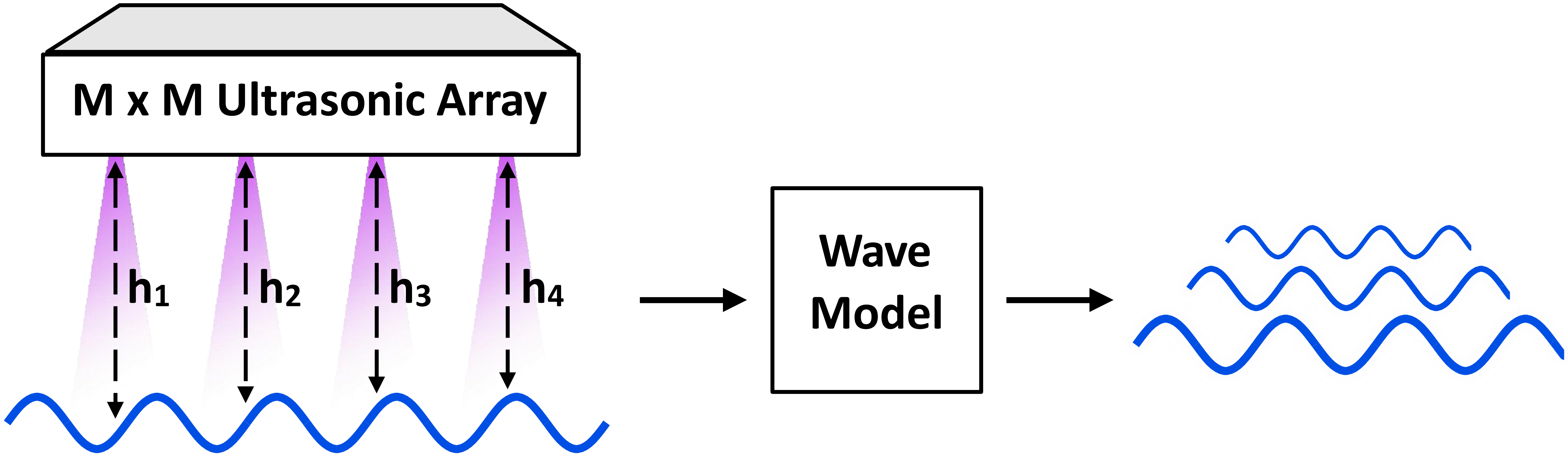
Ultrasonic waves reflect off surface

Bidirectional solution

Design: Dealing with Wave Dynamics



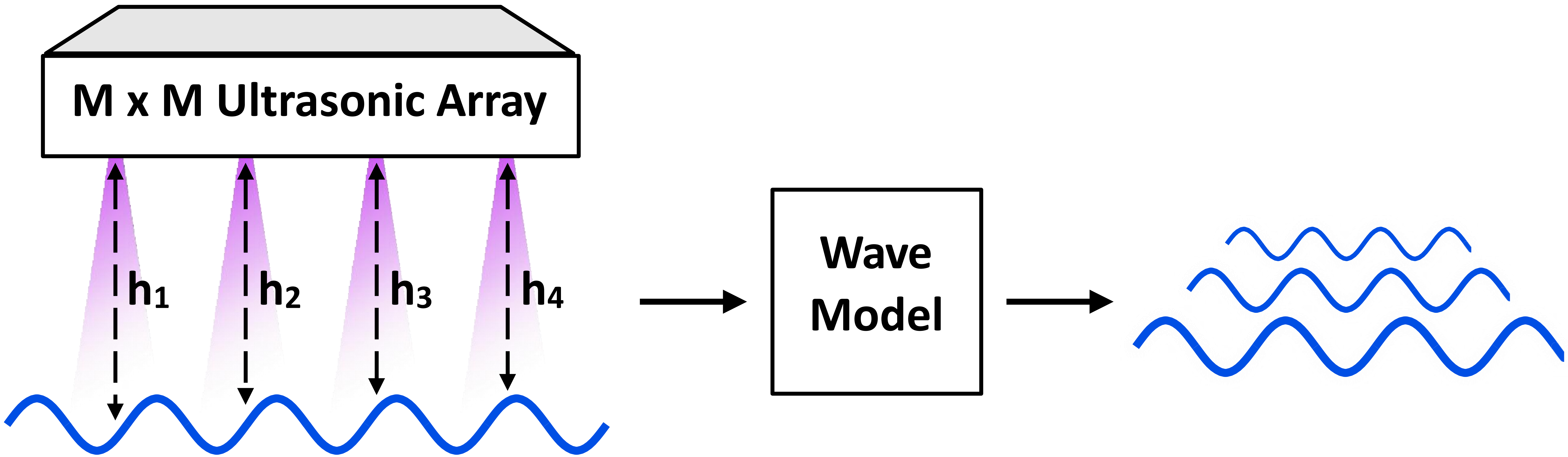
Design: Dealing with Wave Dynamics



✗ Sequential sampling leads to large sensing delay

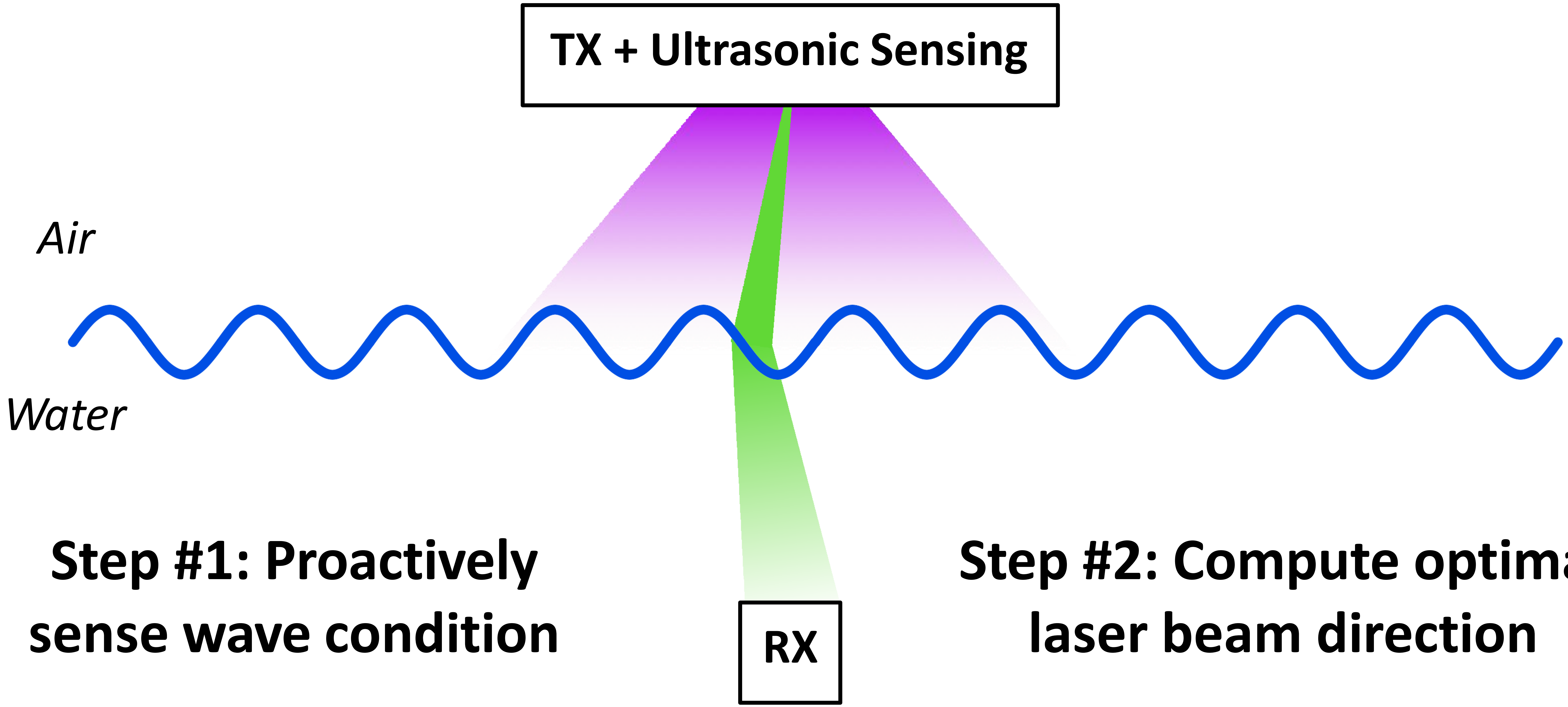
Design: Dealing with Wave Dynamics

- Not wait for all sensor readings to reconstruct waves
- Forecast upcoming sensor readings with FFT



✔ **With forecasting, continuously reconstruct wave**

Design: Dealing with Wave Dynamics



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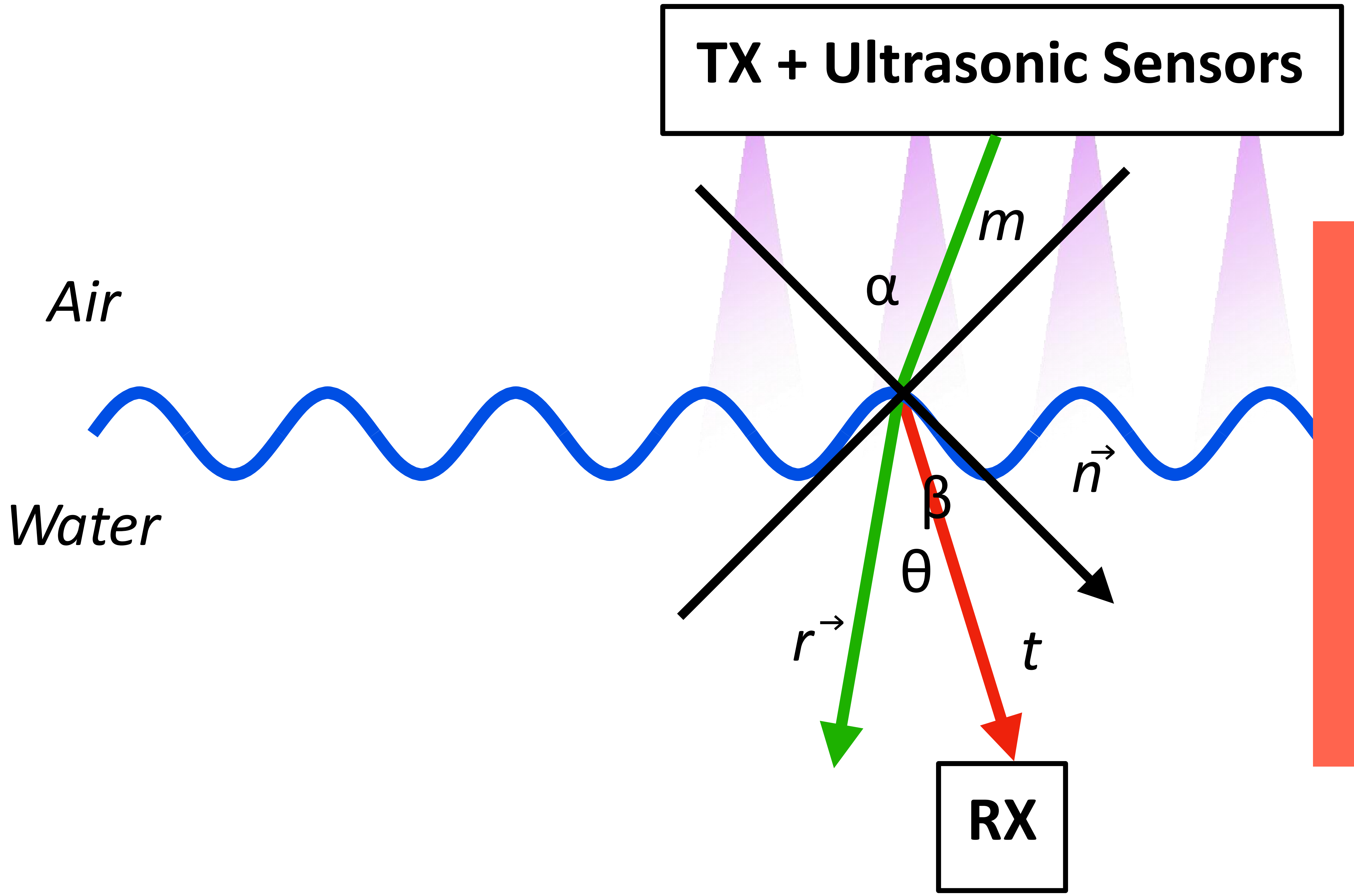
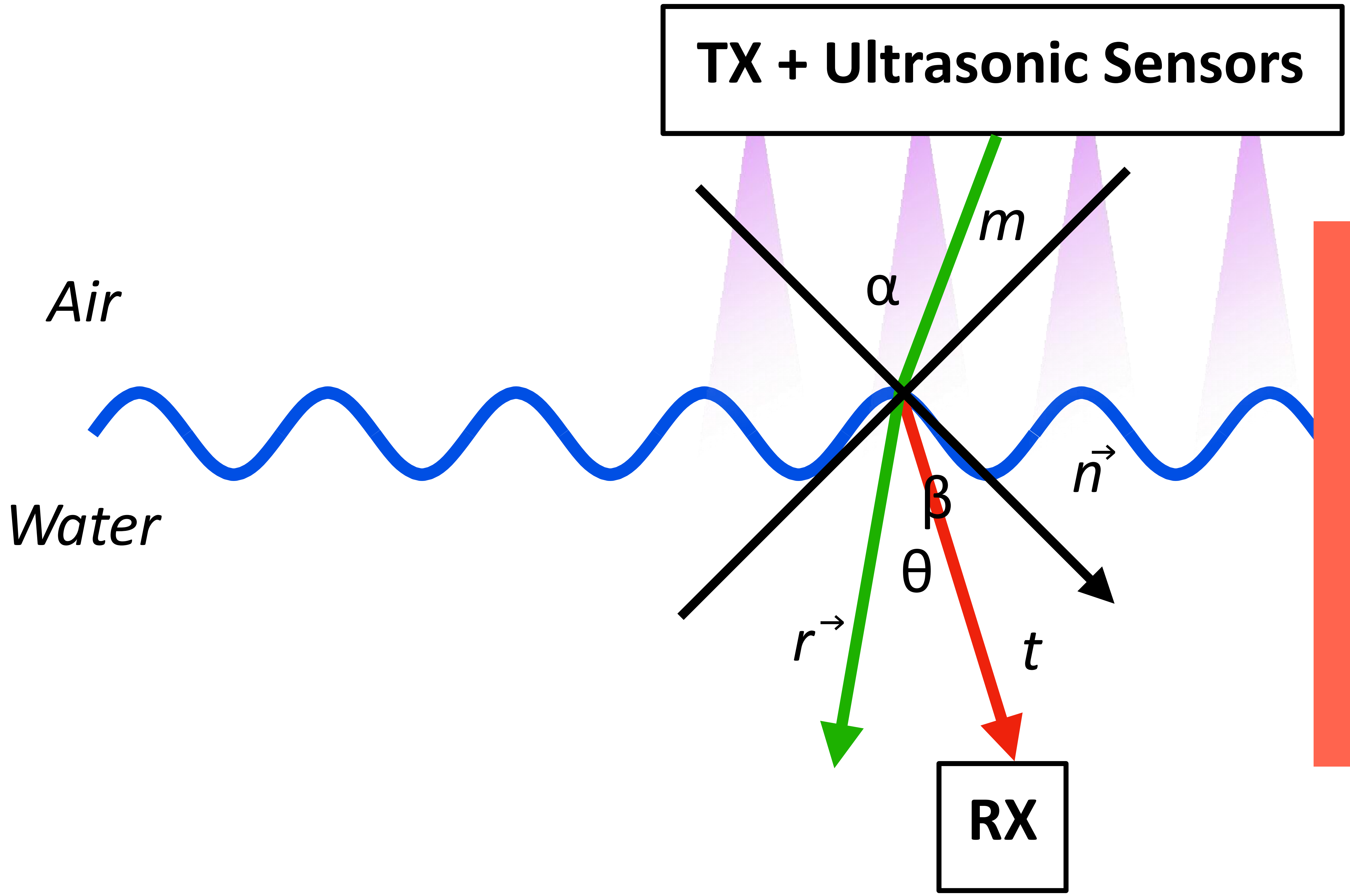
Design: Dealing with Wave Dynamics



Goal: minimize θ between refracted ray and receiver

Design: Dealing with Wave Dynamics



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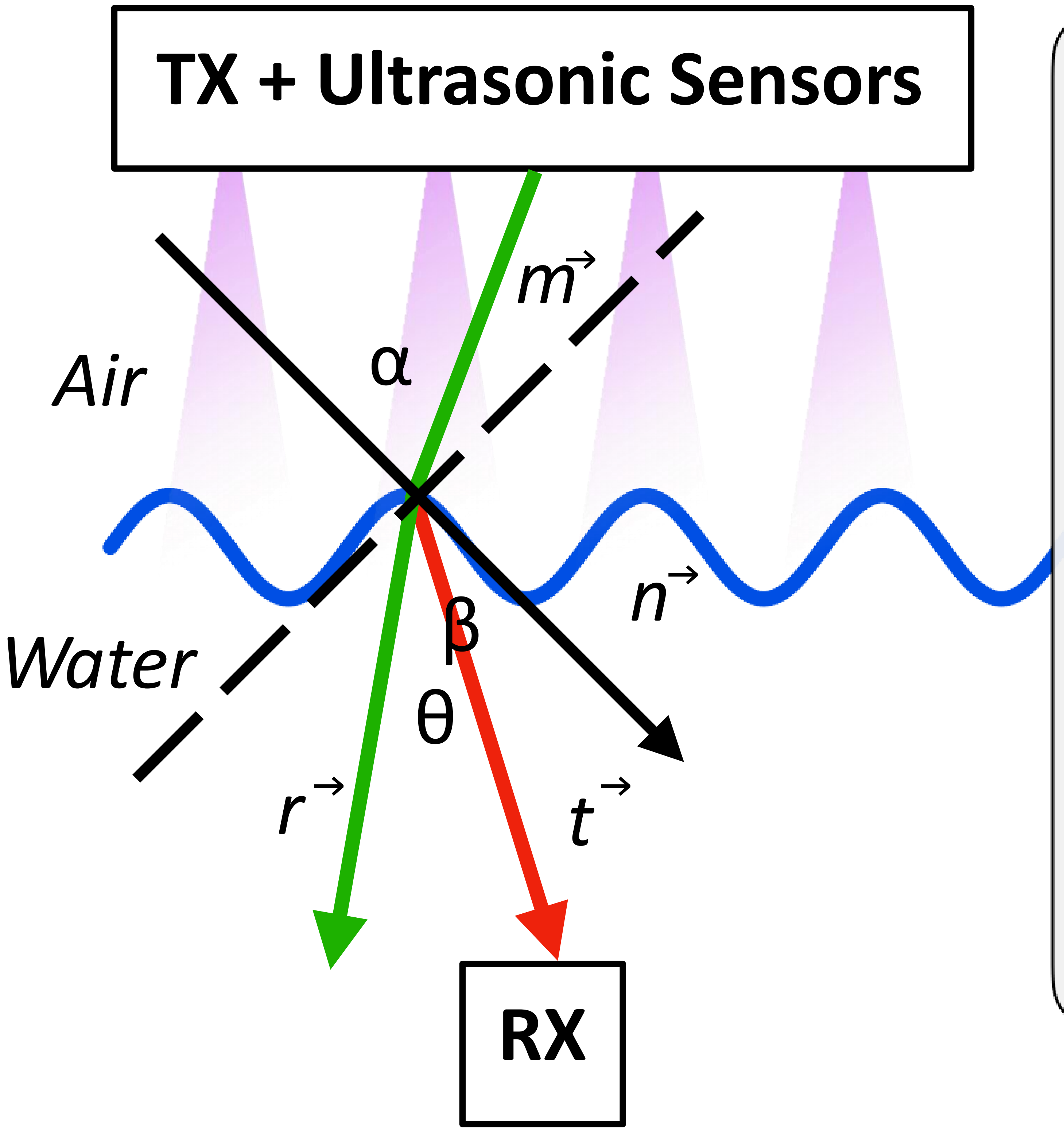


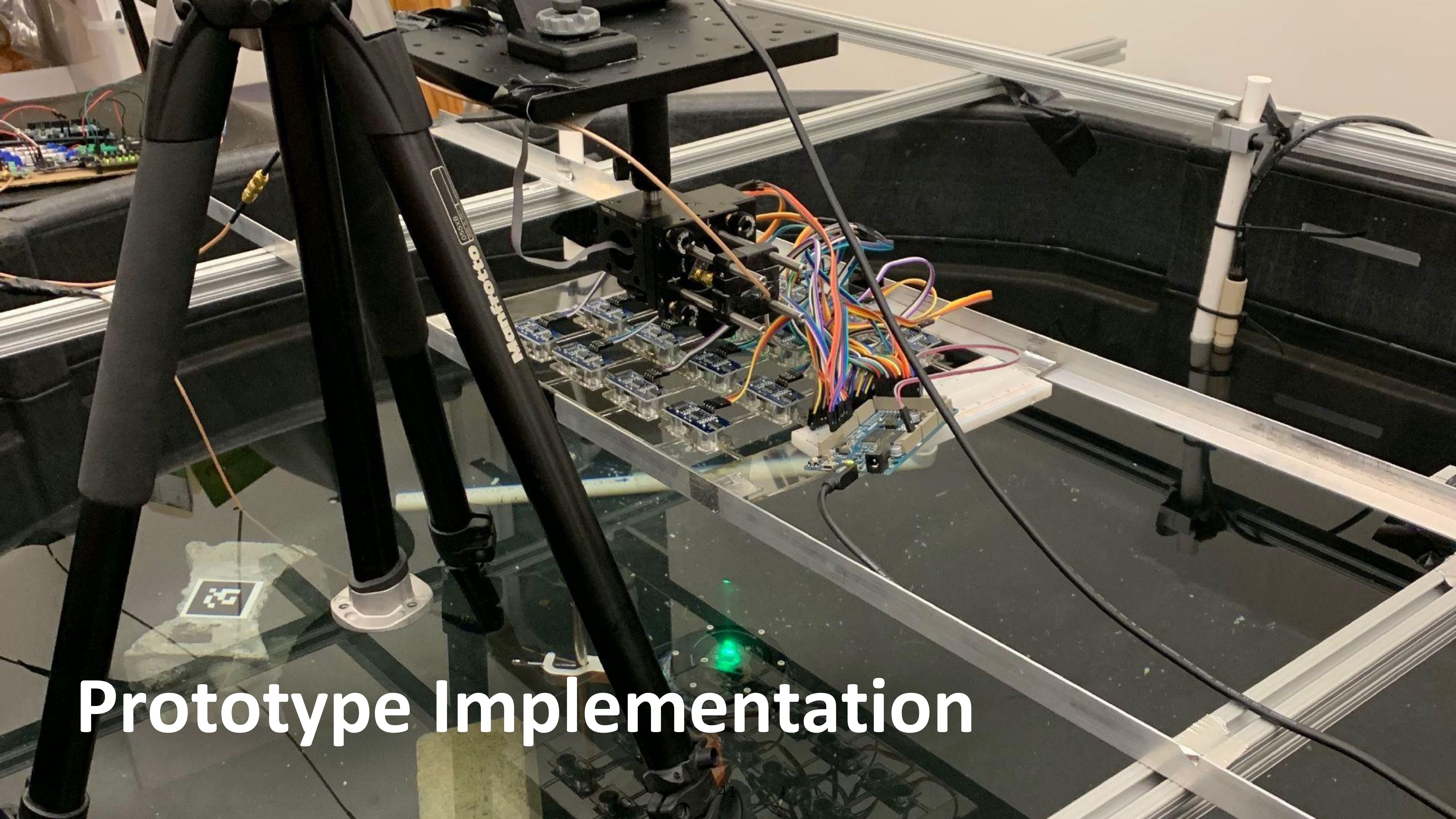
Maximize: $\cos\theta = \dfrac{r \cdot t}{|r||t|}$ (i.e., minimize θ)

Subject to: $r = pm + n$ (refracted light's direcMon)

$p = \dfrac{p|m|}{|n|} = \dfrac{\sin\beta}{\sin(\alpha - \beta)}$ (Snell's Law)

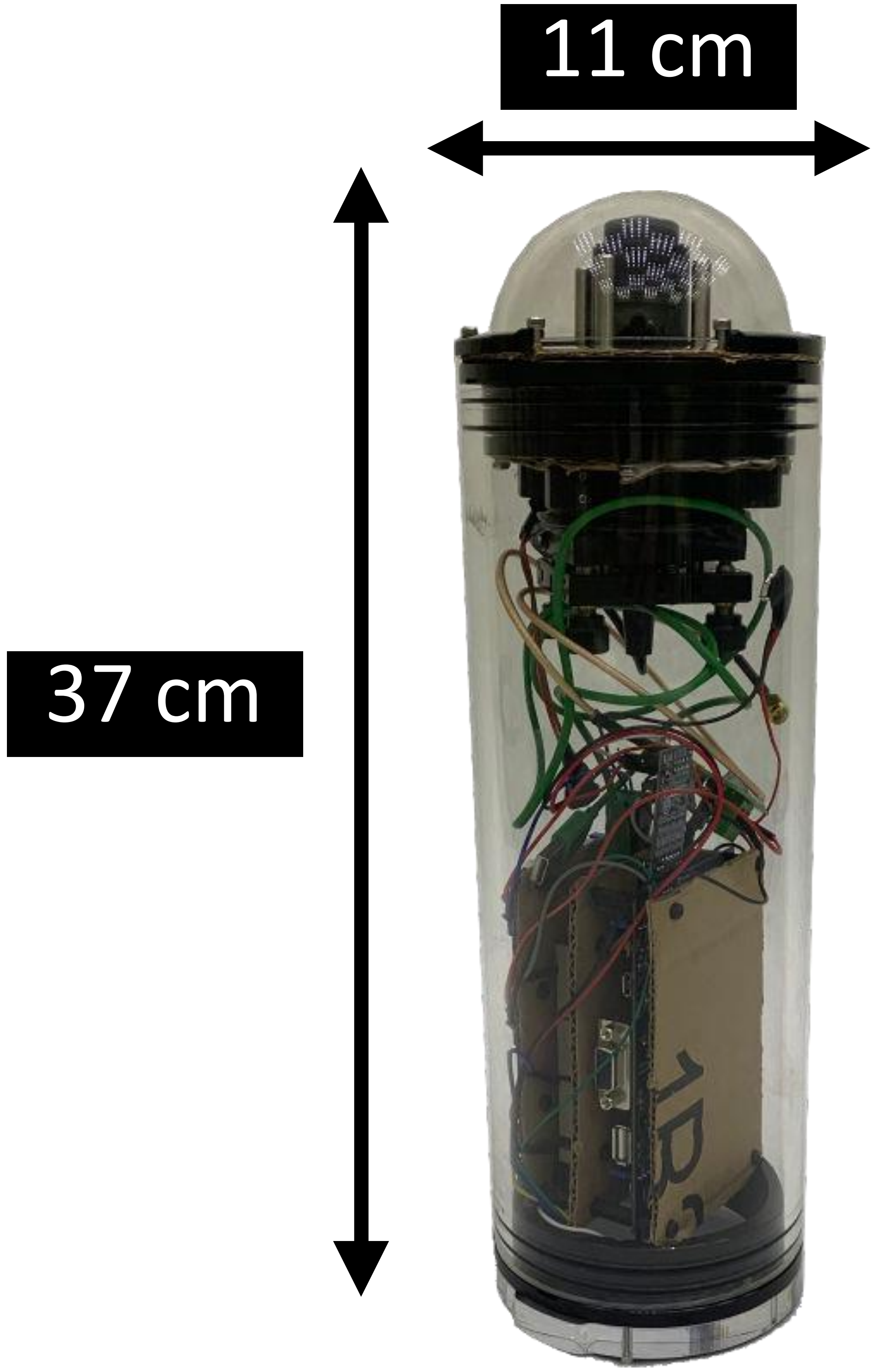
$n = \dfrac{\partial h}{\partial x}, \dfrac{\partial h}{\partial y}, -1$ (surface normal)

Solved with gradient ascent, <1ms



Prototype Implementation

Prototype: Transmitter



Transmitter

Laser Diode

- 140 mW, 520 nm

DarkLight Modulation

- 13.7% duty cycle OPPM

MEMS Mirror

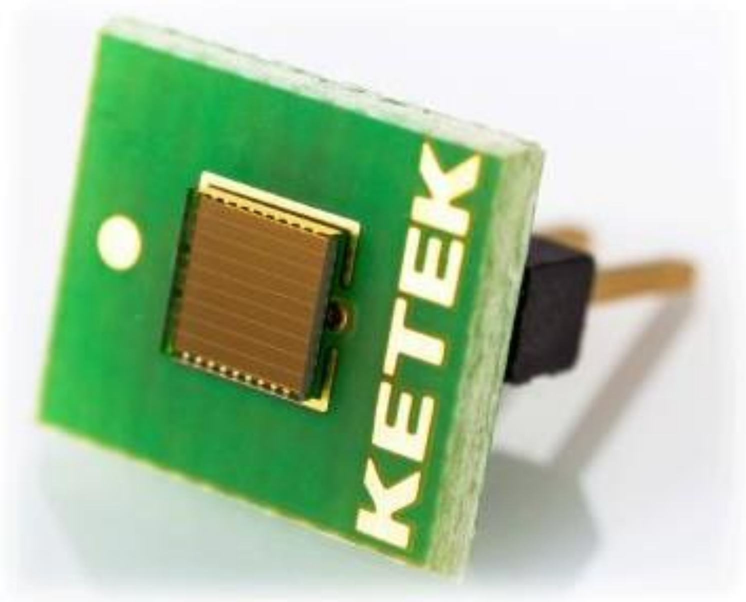
- 130 Hz, 0.003° resolution, ±6.6° range

Prototype: Receiver

Receiver

SiPM

- 3mm x 3mm active area
- 180° sensitivity

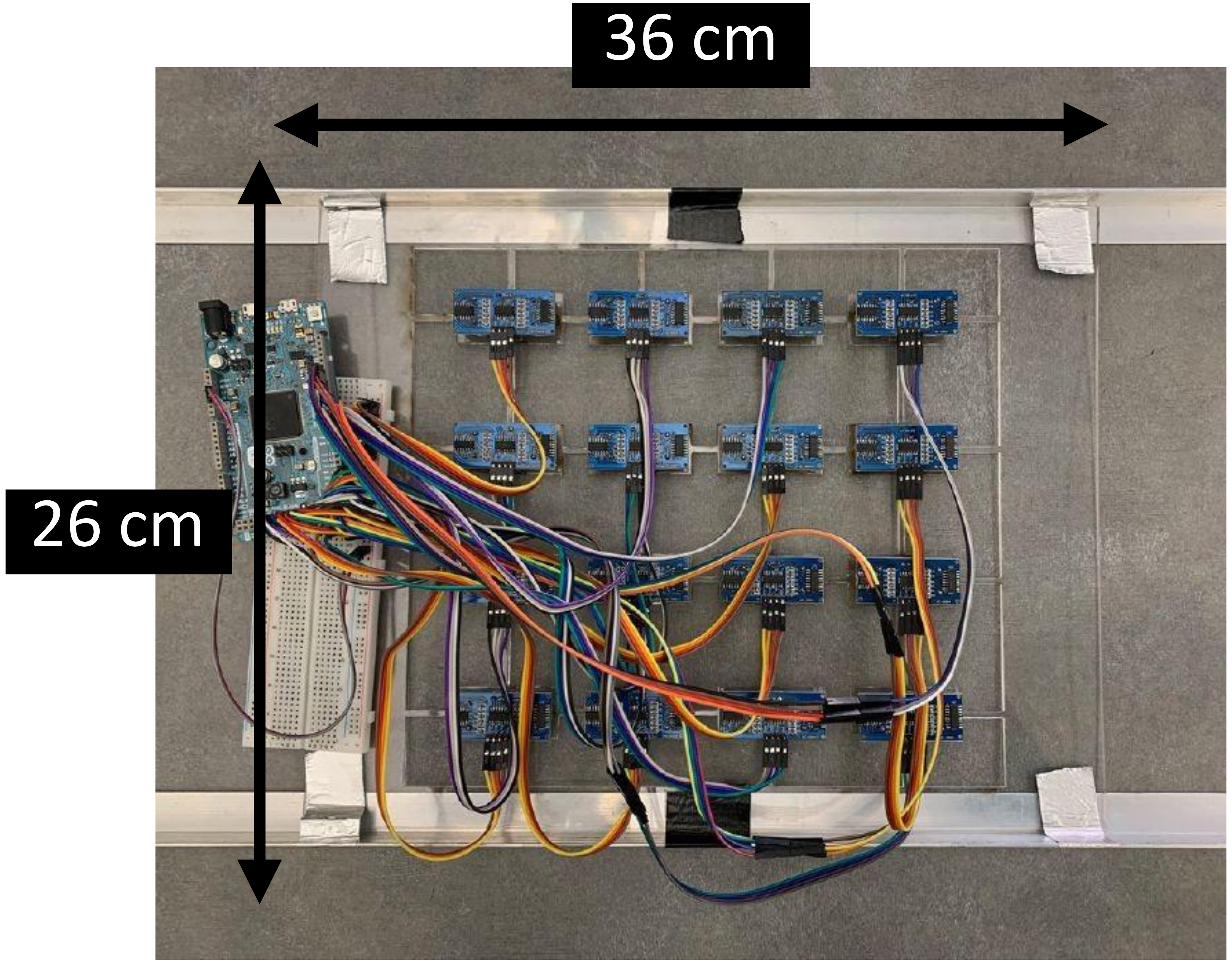


Oscilloscope

- Keysight 2.5 GHz, 20 GSa/s

Image Courtesy of Ketek

Prototype: Ultrasonic Array



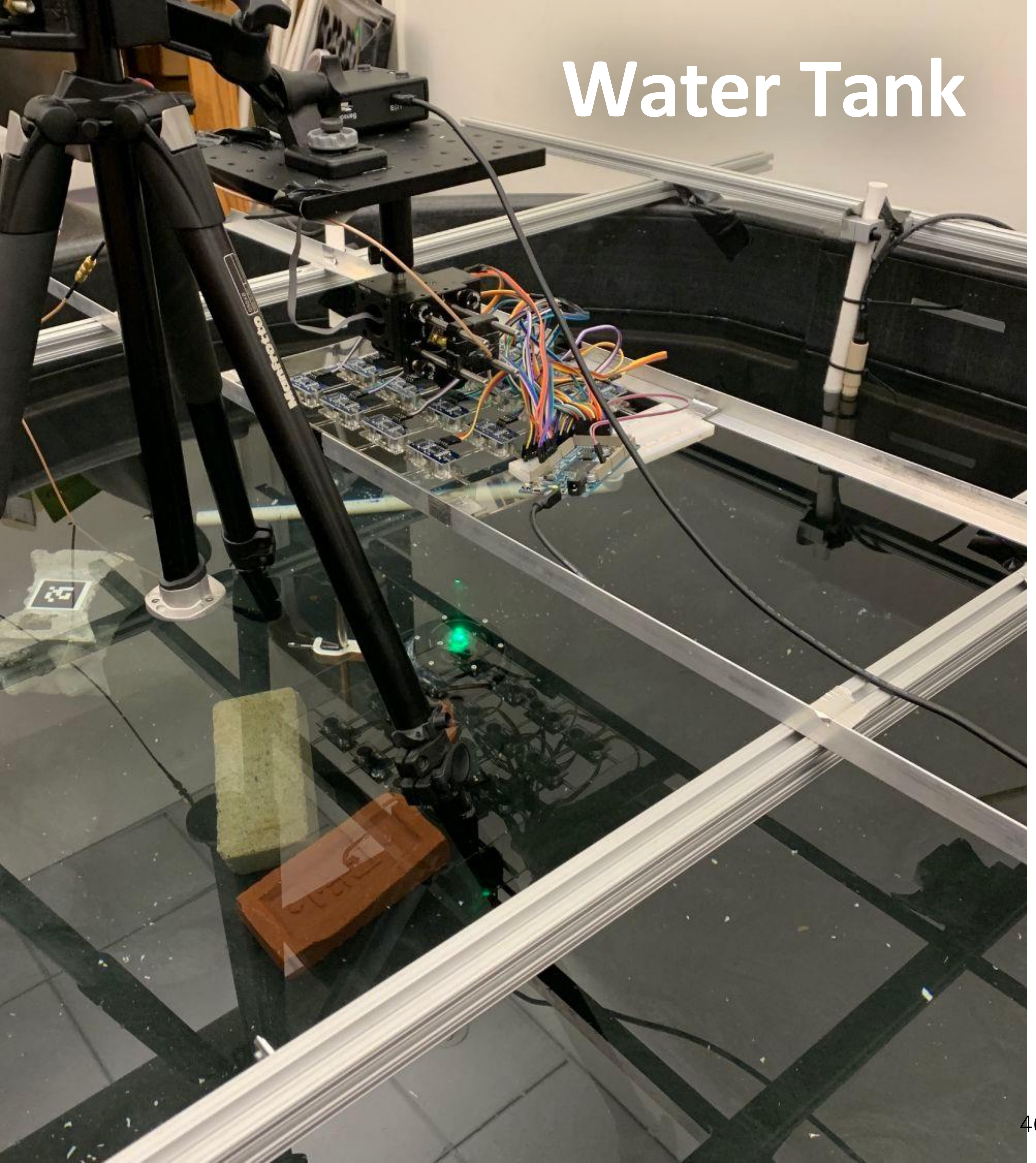
Top

Ultrasonic Array

- $4/sensor
- 15° beam angle
- Accuracy up to 3 mm

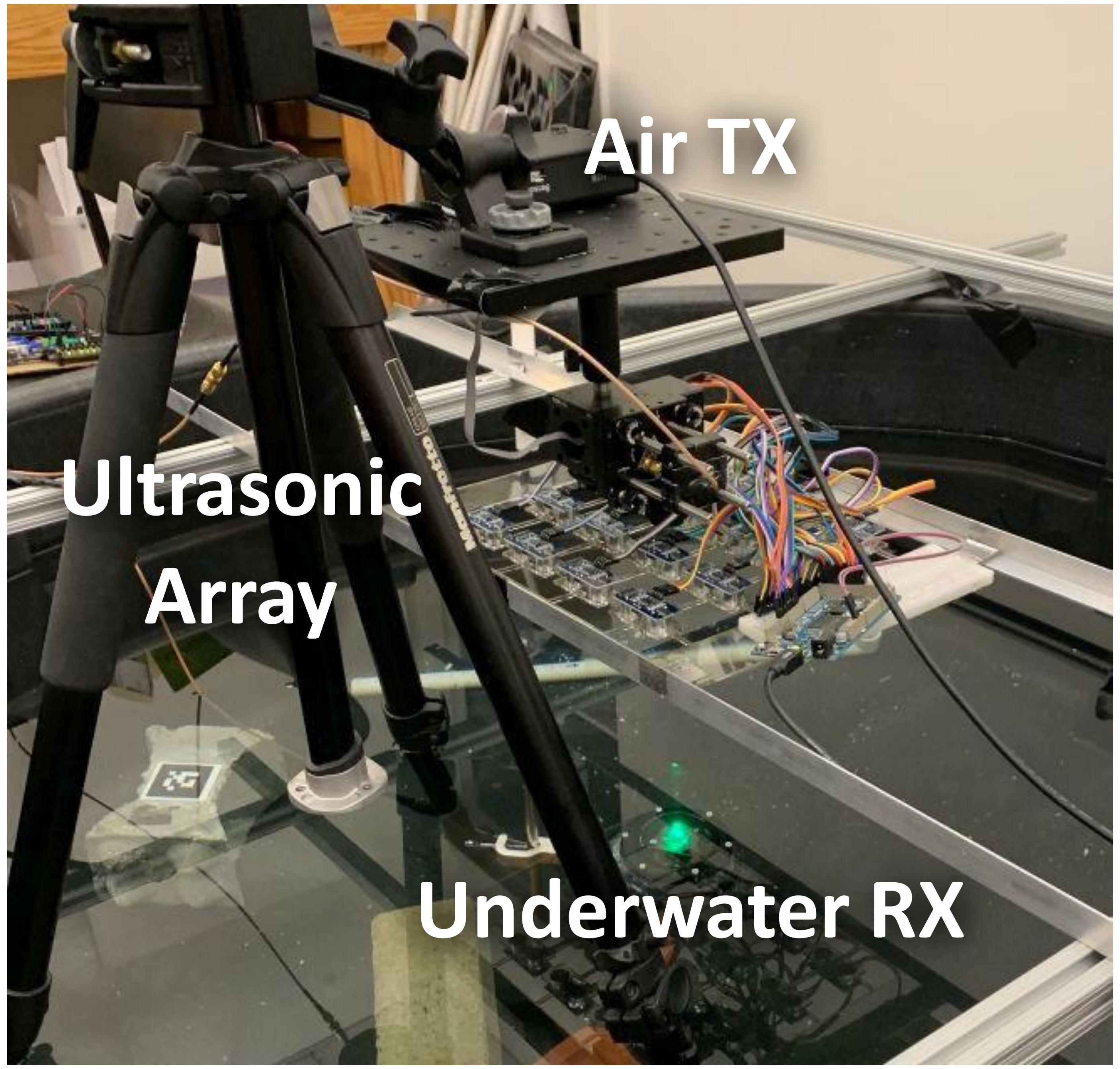
System Evaluation

- Link performance
- Link robustness

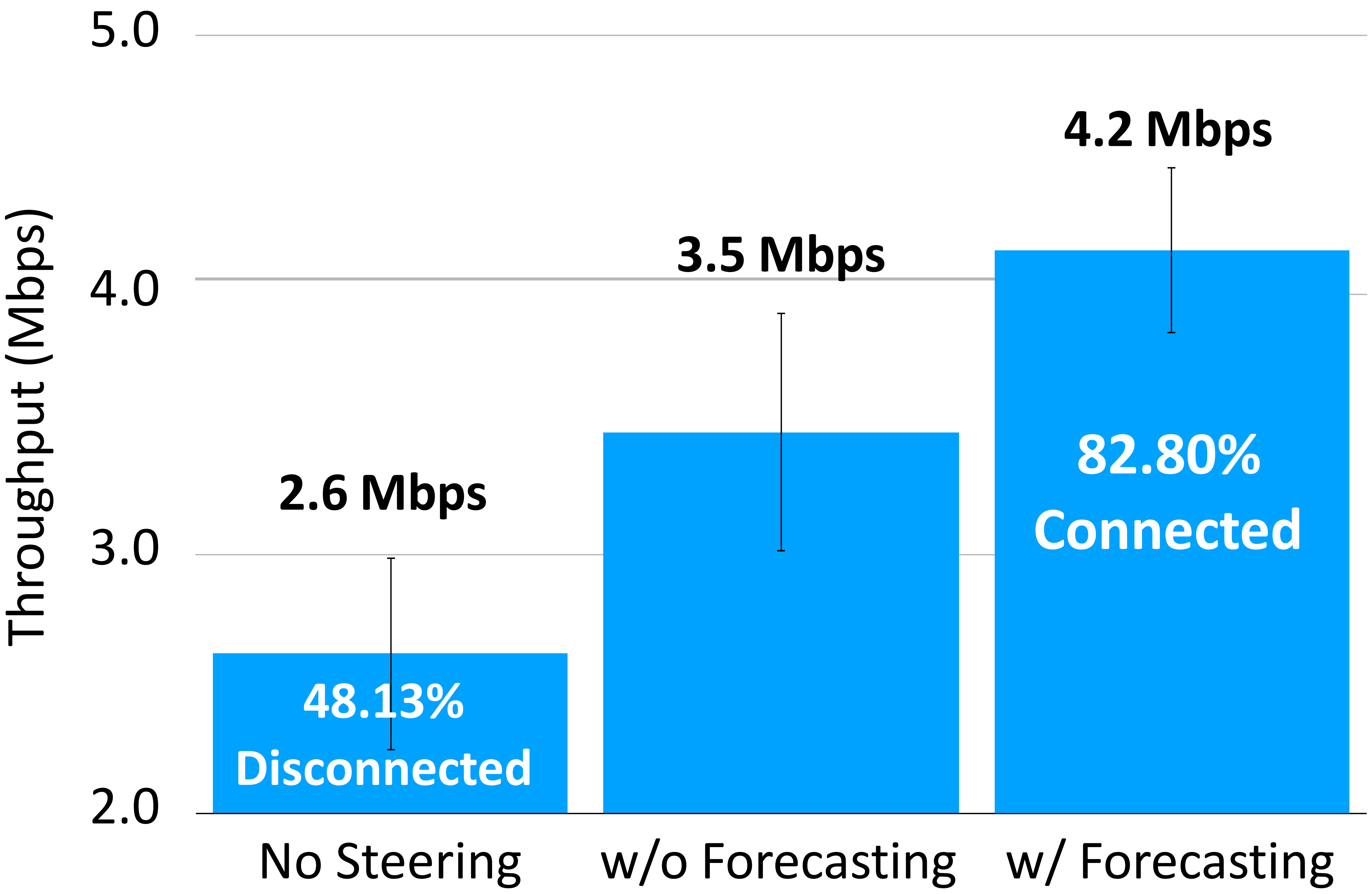

Water Tank


THE GIFT OF
1919
Swimming Pool

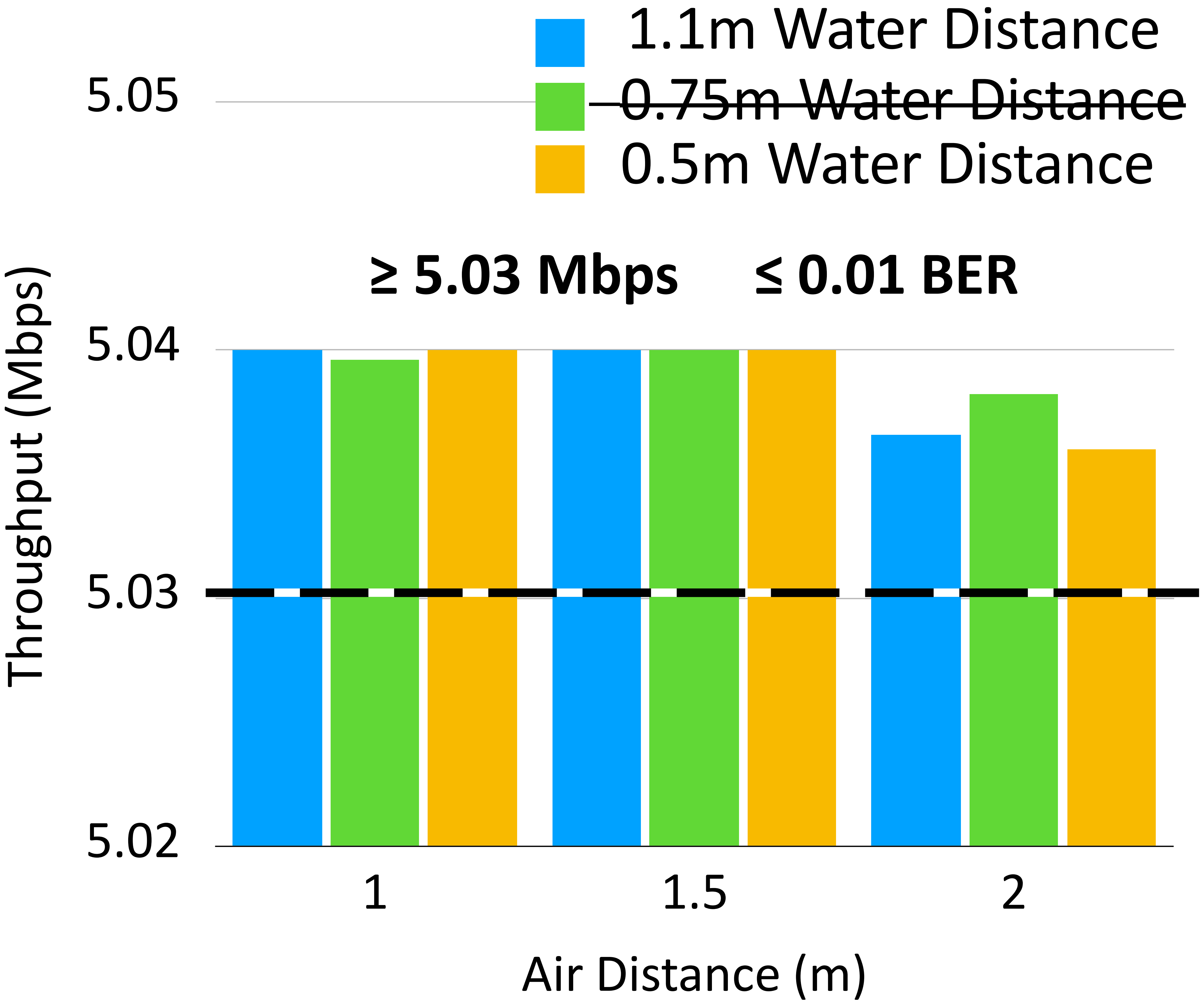
Evaluation: Throughput



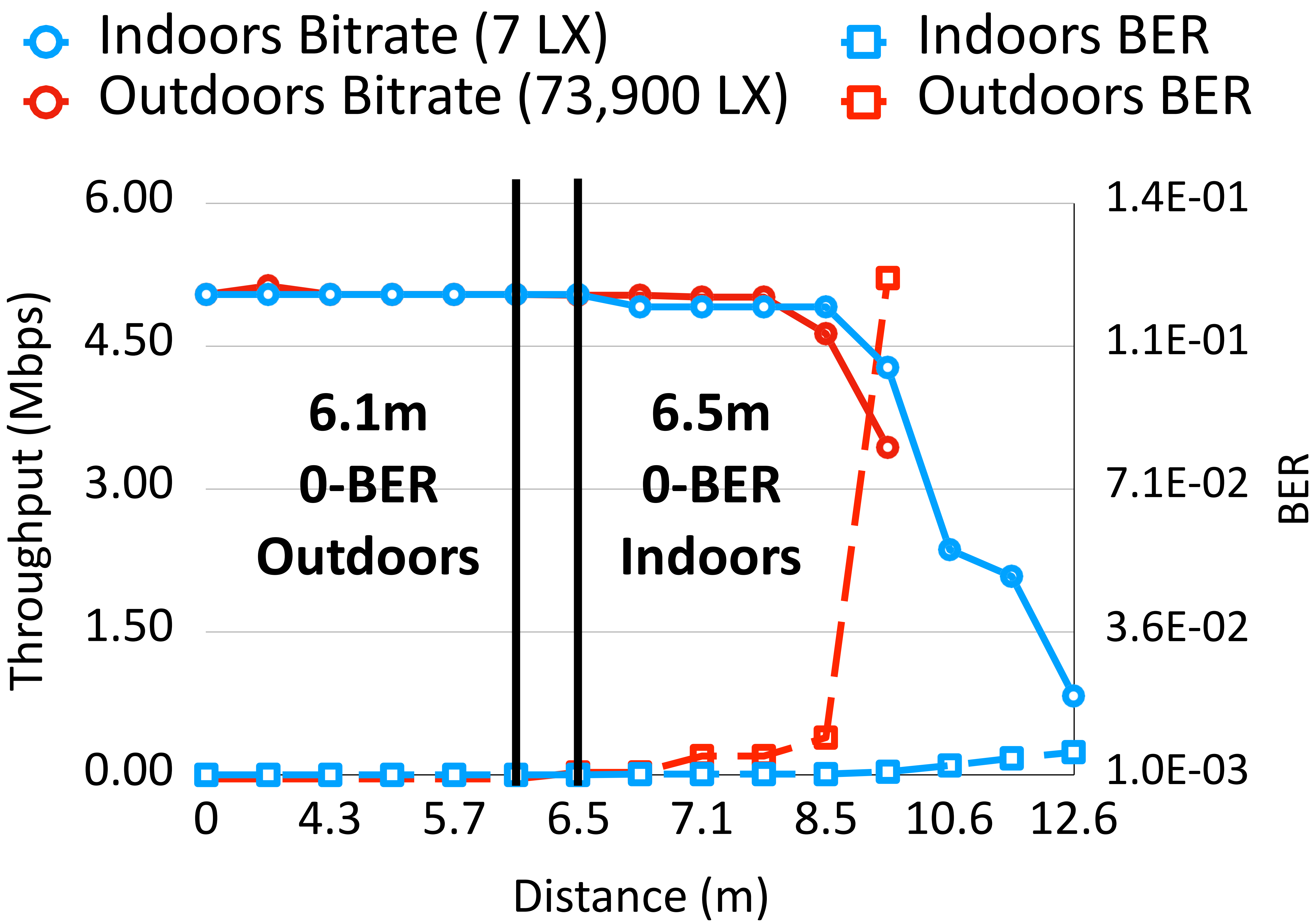
Waves: 10–12 cm, 1 Hz



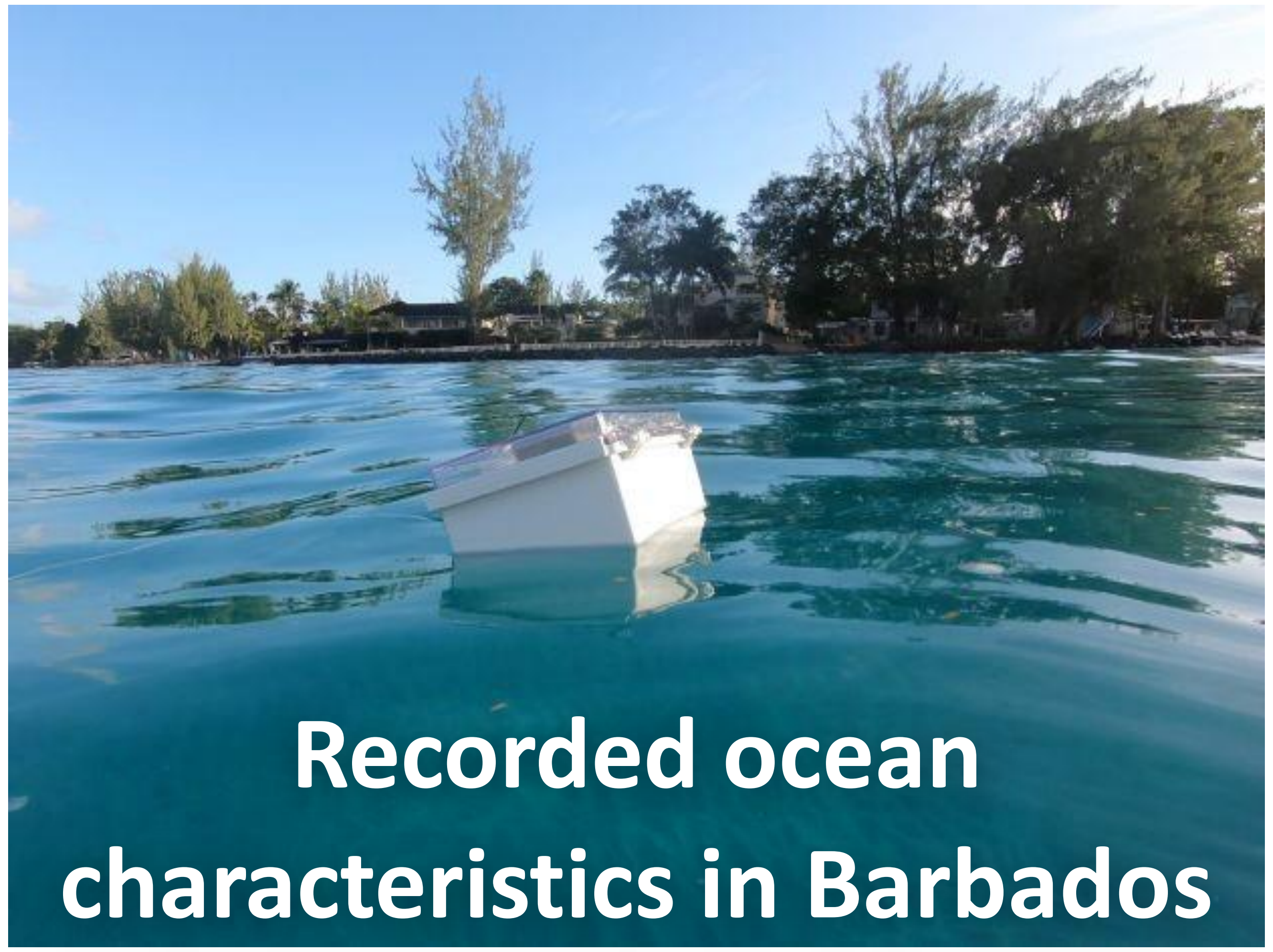
Evaluation: Range



Evaluation: Ambient Light Robustness

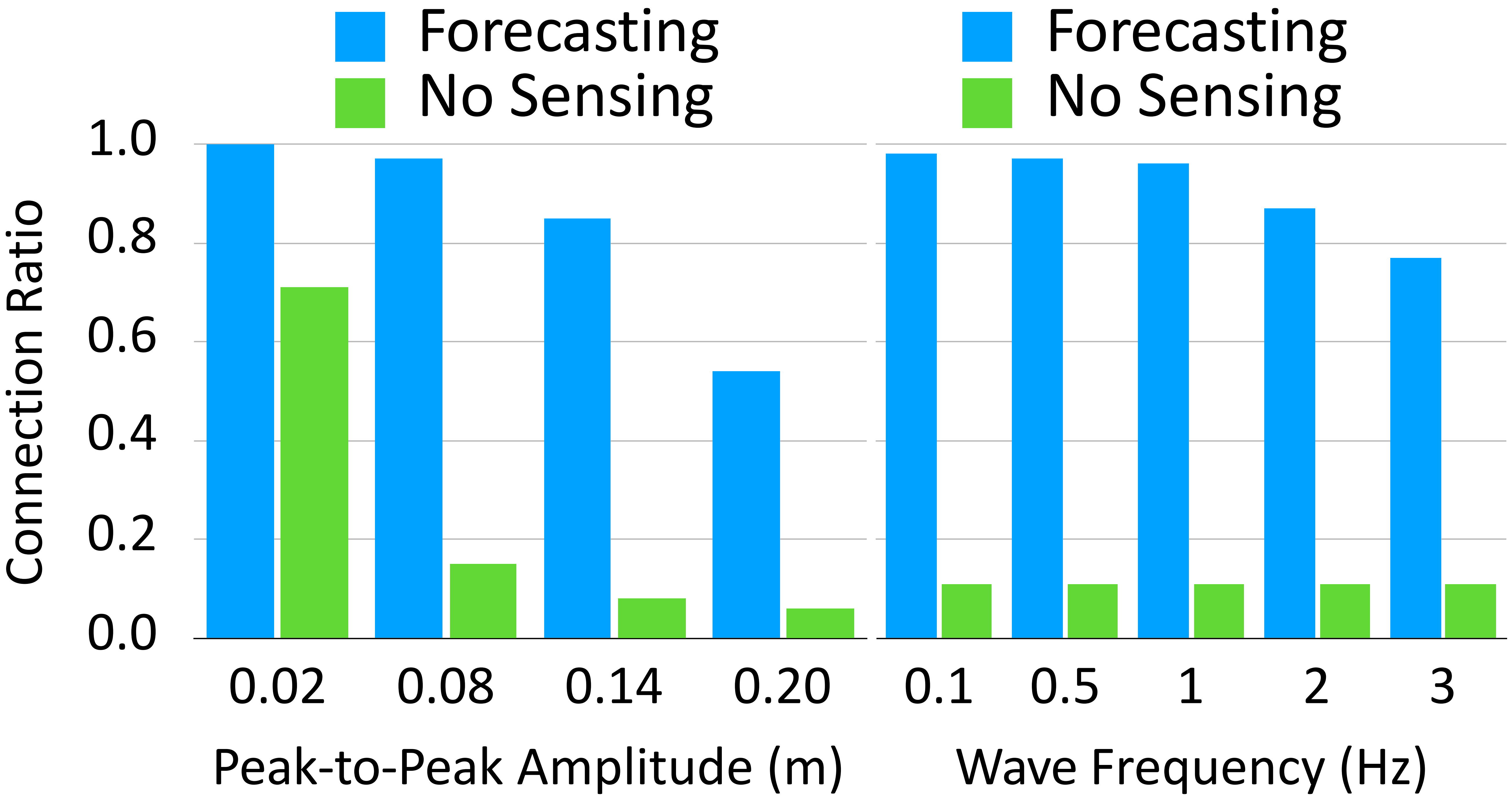


Evaluation: Wave Robustness



Peak-to-peak amplitudes: 2–20 cm

Wave frequencies: 0.1–3 Hz



Reliability decreases at large amplitudes

Consistently ≥ 75% reliable

Discussion & Conclusion

- **Mobility**
- **Dispersion**
- **Occlusion**
- **Sampling Method**