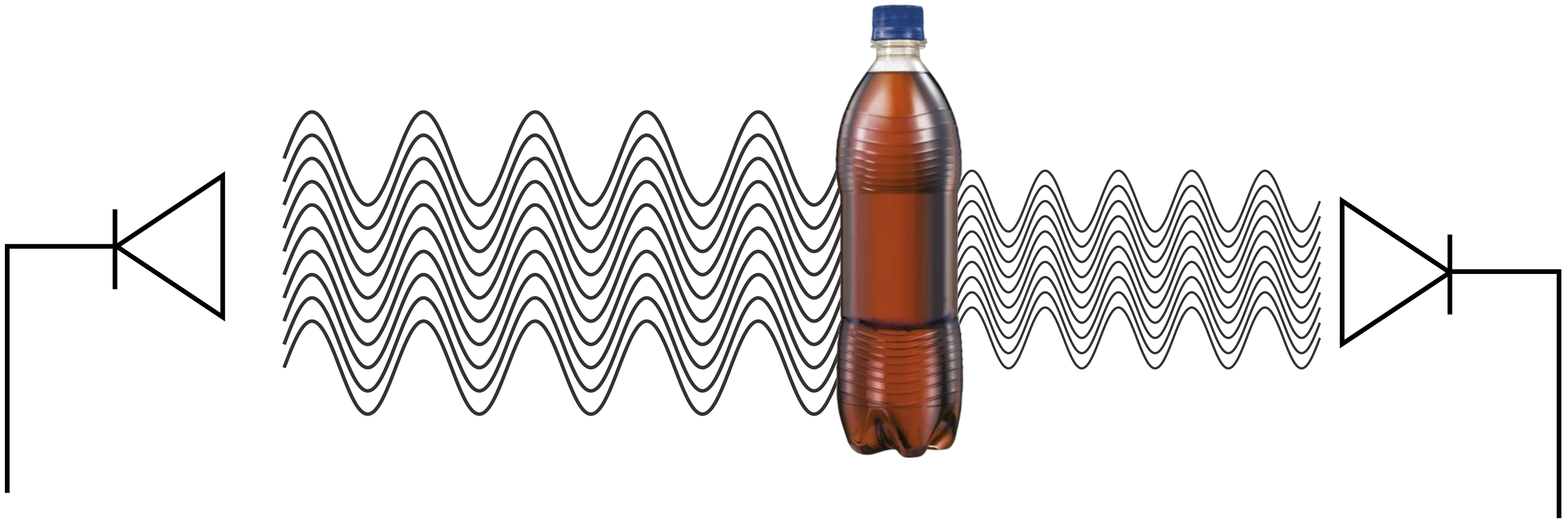
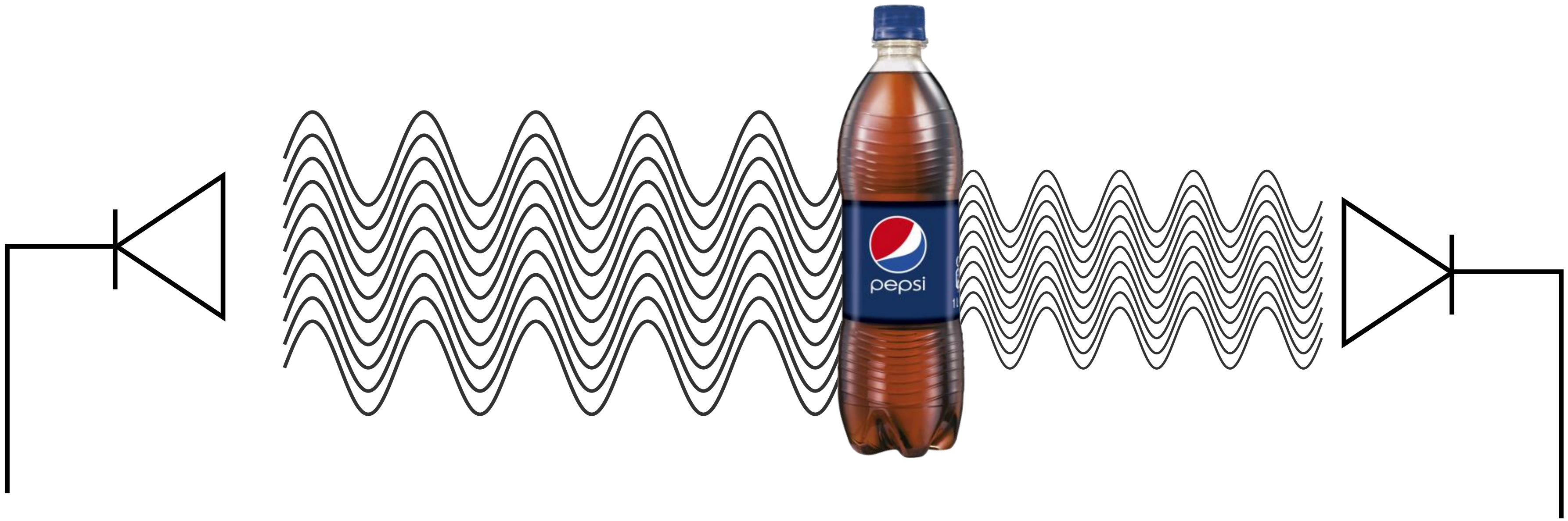
LiquID: A Wireless Liquid IDentifier

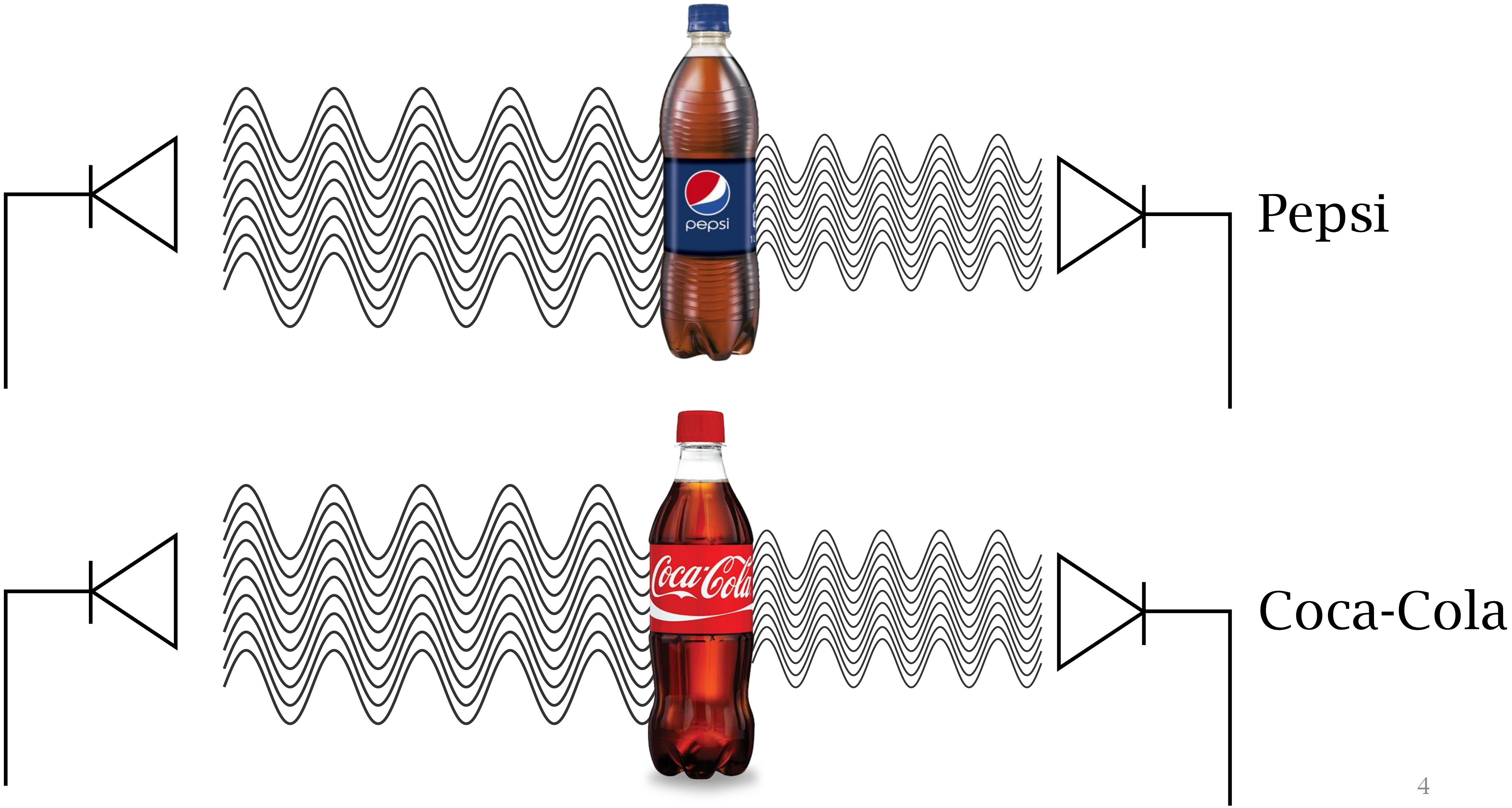
Ashutosh Dhekne, Mahanth Gowda, Yixuan Zhao, Haitham Hassanieh, Romit Roy Choudhury

University of Illinois, Urbana-Champaign



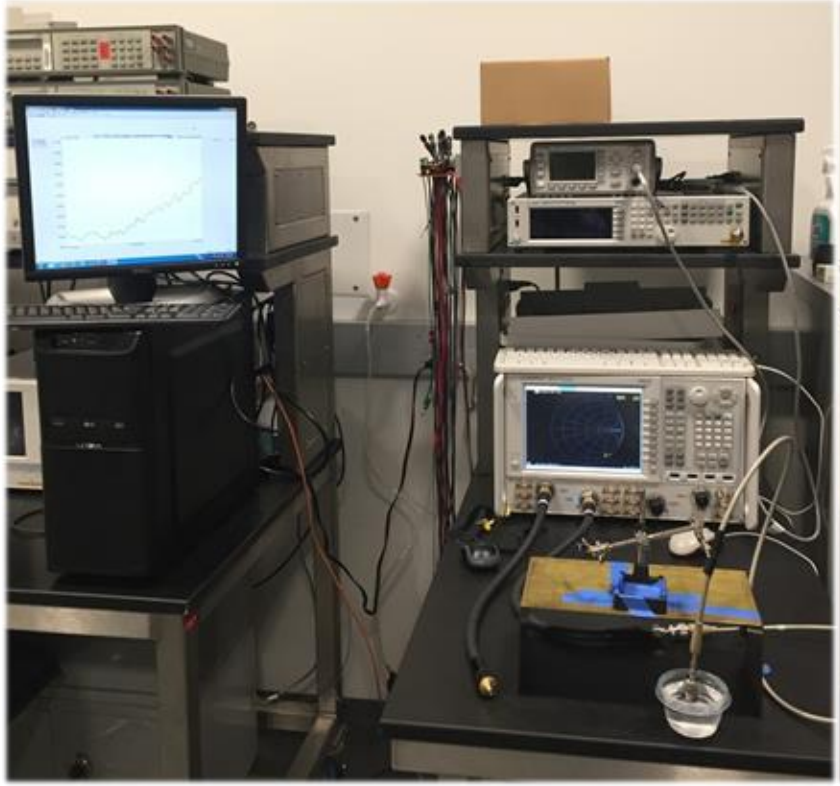


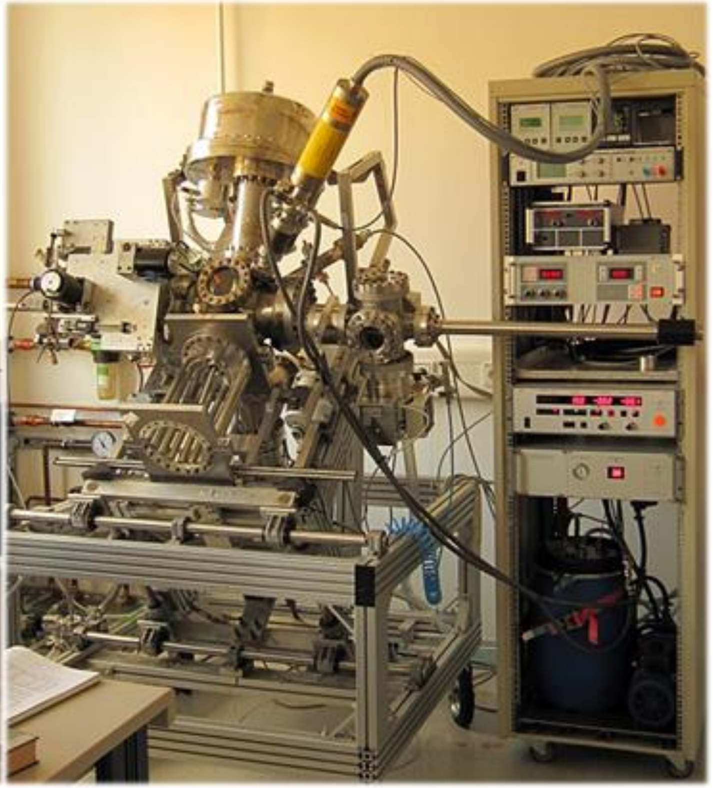
Pepsi


Pepsi
Coca-Cola

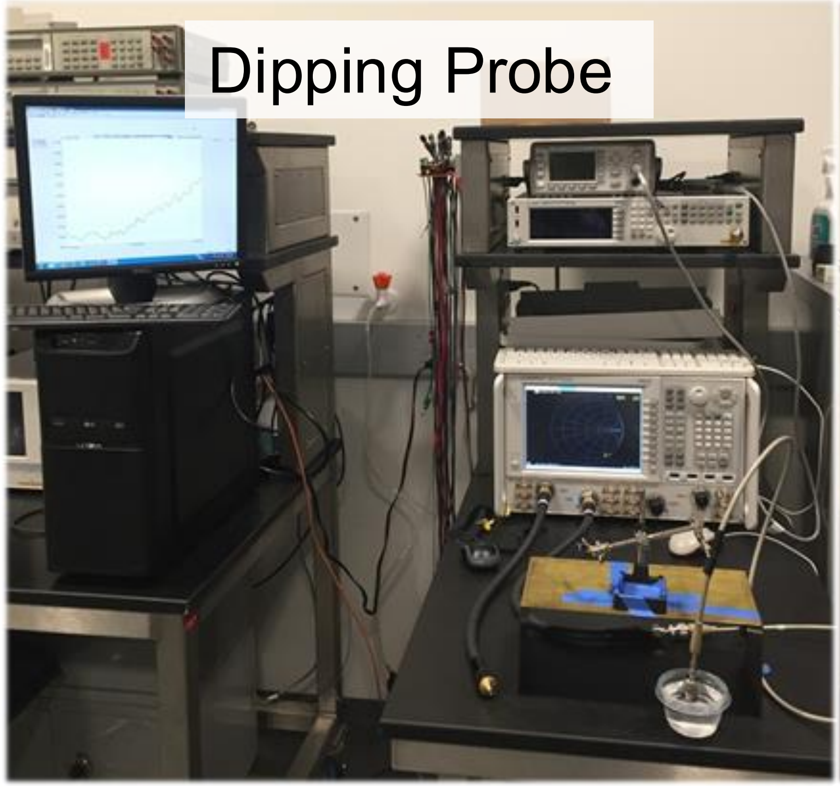

pepsi
diet pepsi
MOUNT FRANKLIN
Lightly Sparkling
ORGANIC VALLEY
Vionelli
La Spagnola
Peanut Oil
EXTRA VIRGIN OLIVE OIL
GEORGIA OLIVE FARMS
PENNZOIL
Coca-Cola
zero
AriZona
Ocean Spray
Cranberry
Juice Cocktail
TREE TOP
100% Apple Juice
KEMPS
100% Pure Orange Juice
Welch's
100% Grape Juice
91% Alcohol
CVS Health
Rubbing Alcohol
DISTILLED WATER
AQUAFINA

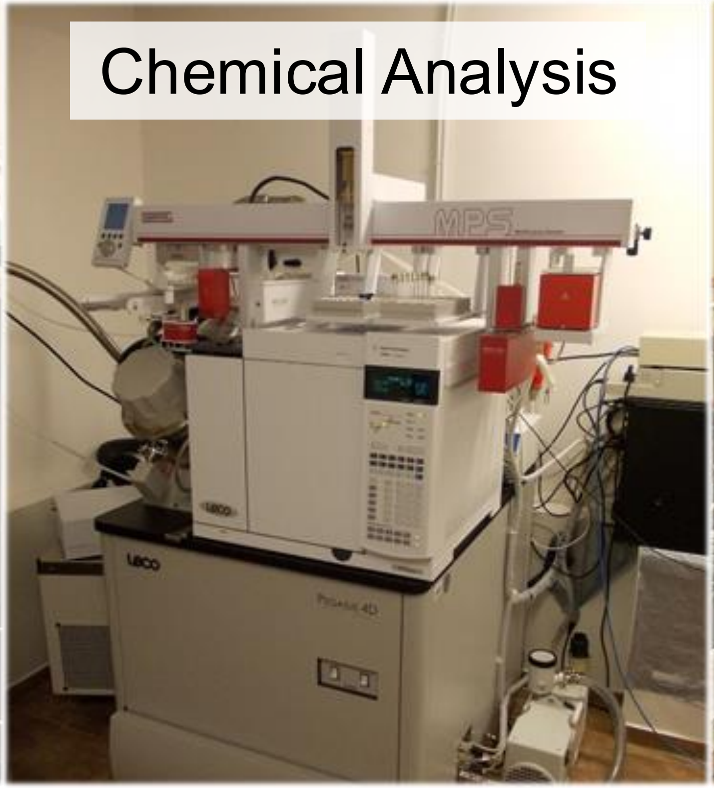
Existing Solutions

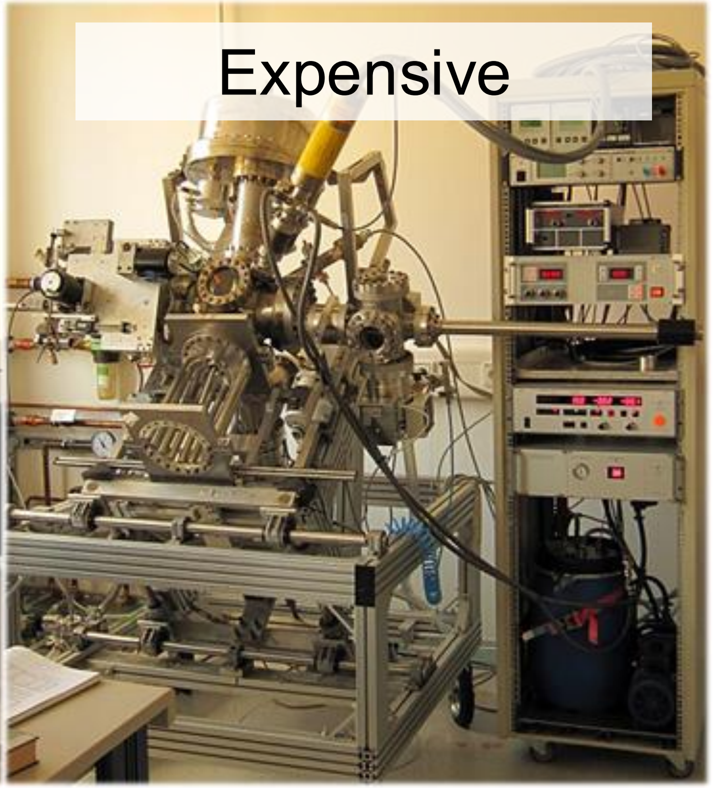




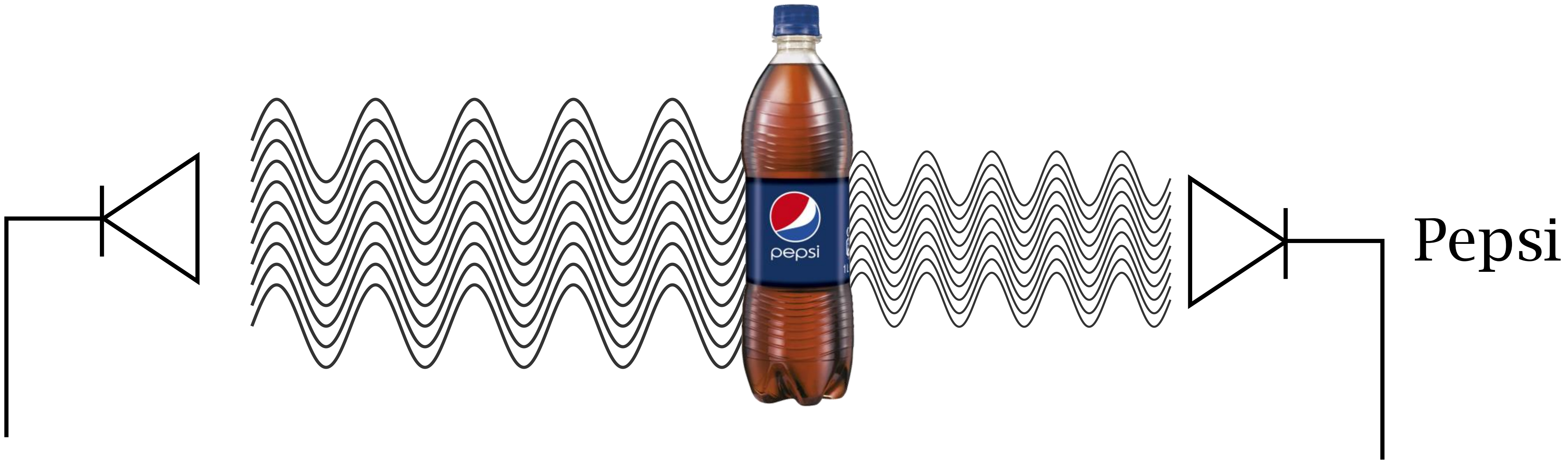
Existing Solutions







Benefits of LiquID

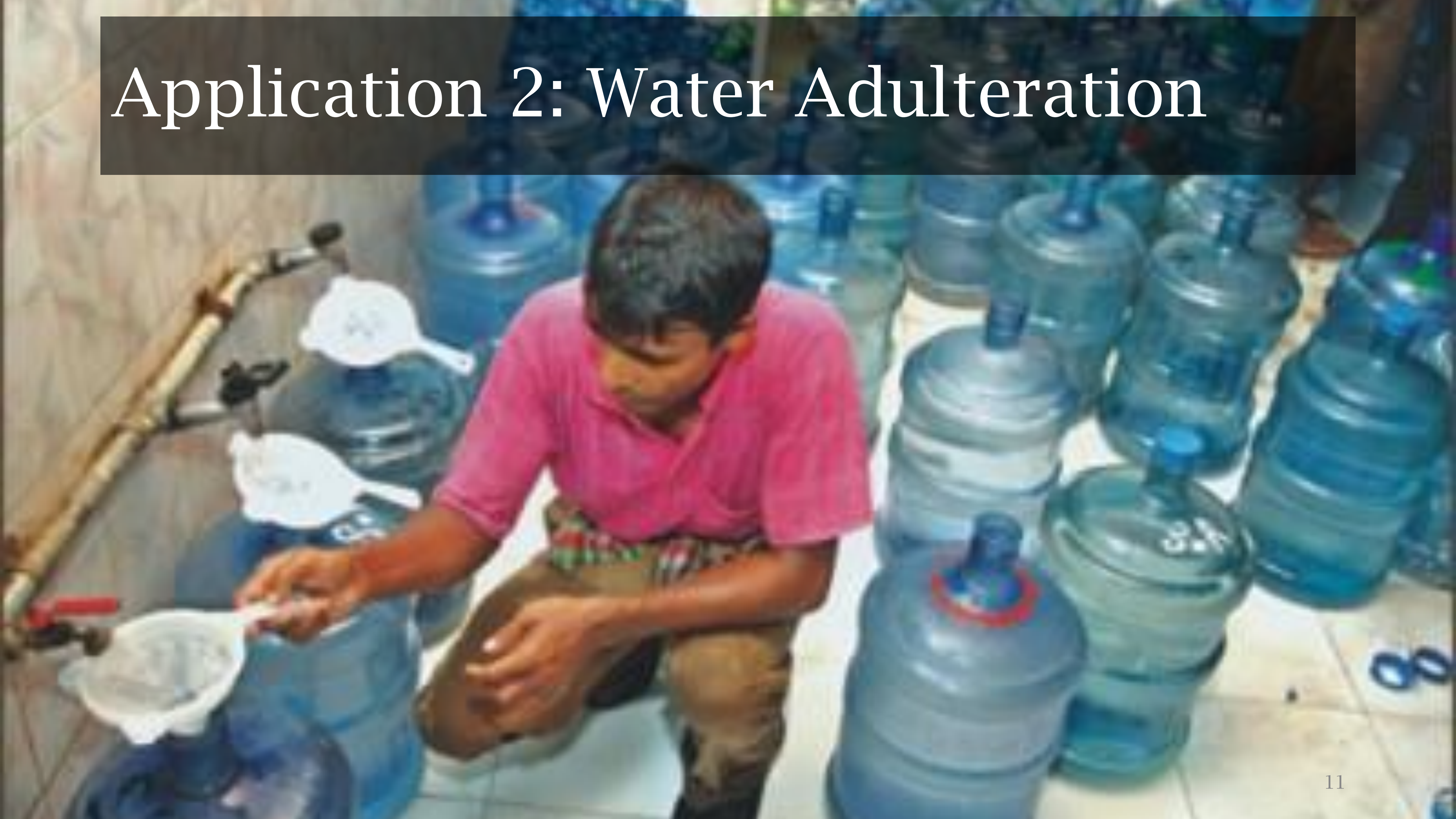


- ✓ Identifies liquid without touching it – Non-invasive
- ✓ Passes wireless signals – Non-destructive
- ✓ Small and inexpensive – Convenient

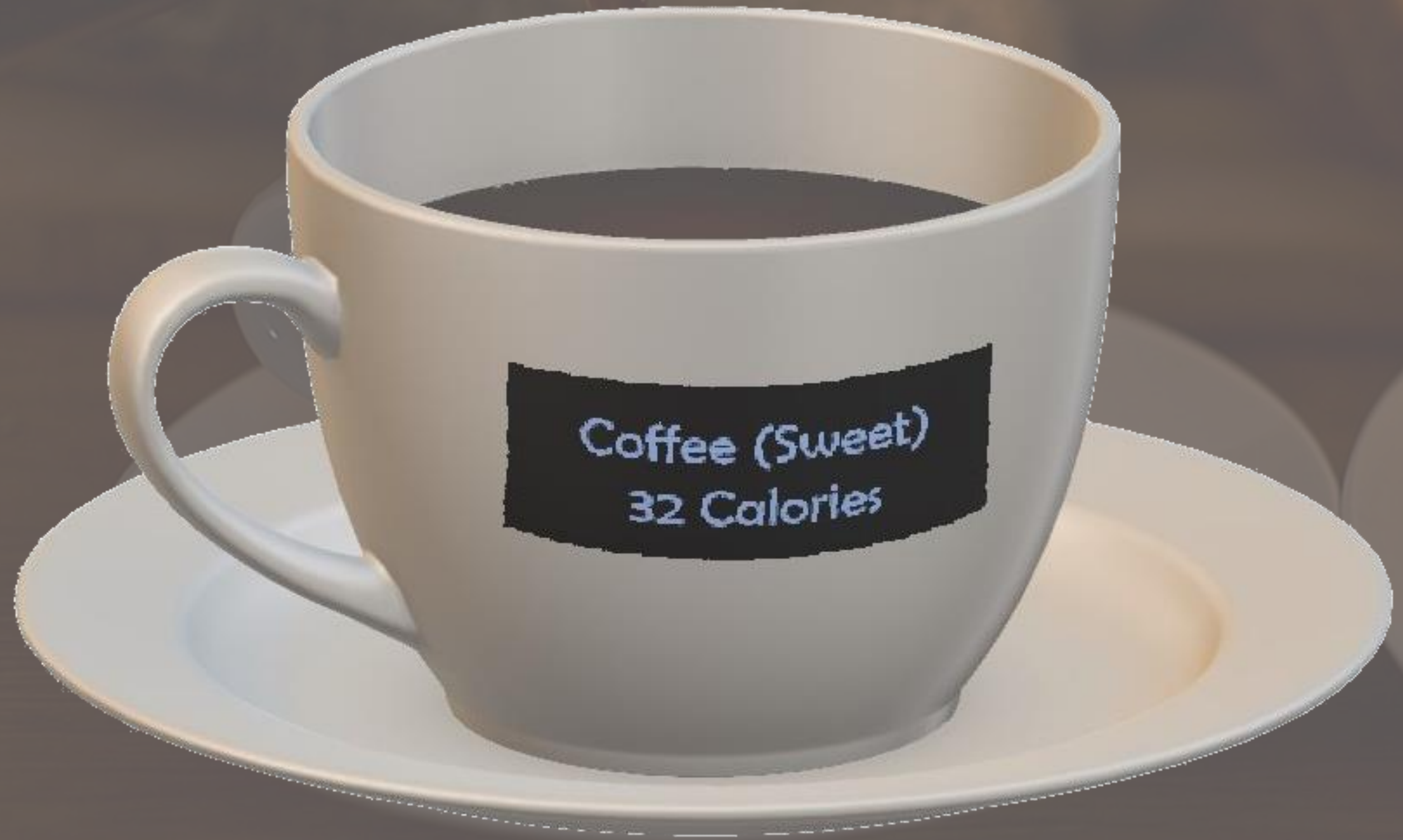
Applications

Application 1: Airport Security

Application 2: Water Adulteration

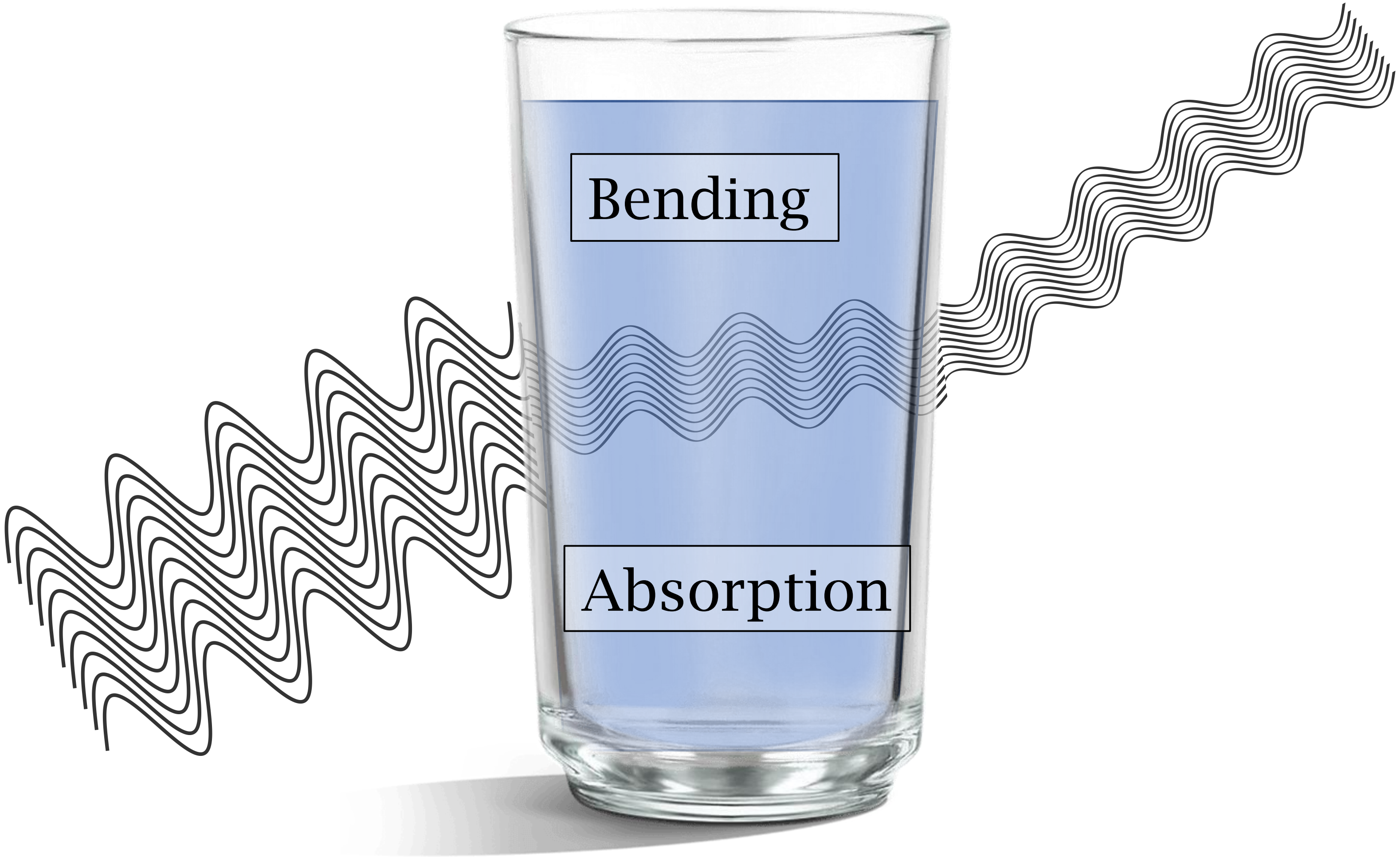


Application 3: Calorie Cup

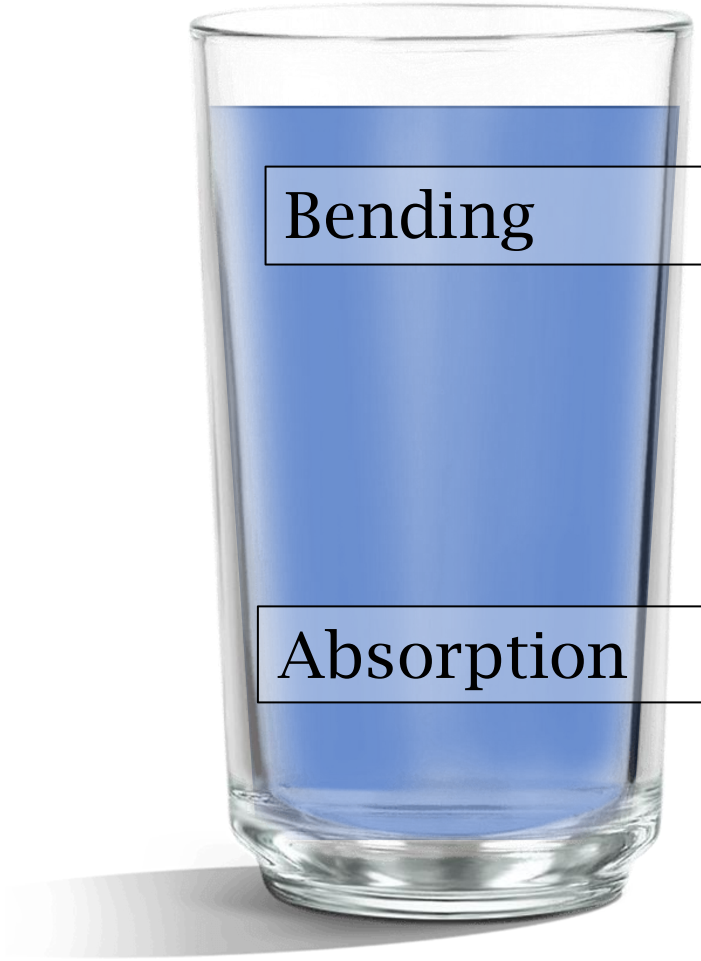


How?

Key Properties of Liquid



Key Properties of Liquid



Bending → Refractive Index

Unique Tuple

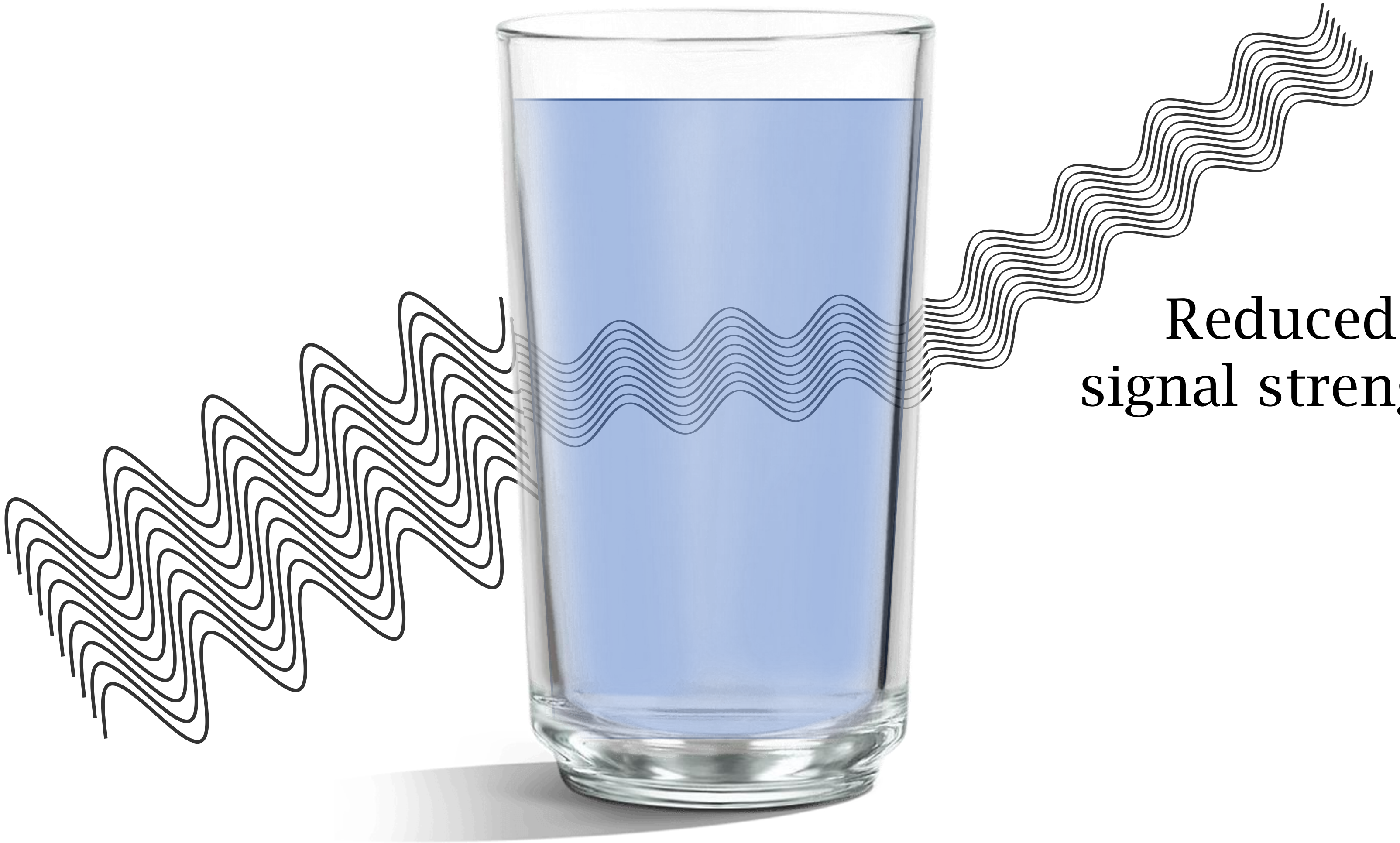
Absorption → Attenuation Factor

Key Properties of Liquids

Refractive index

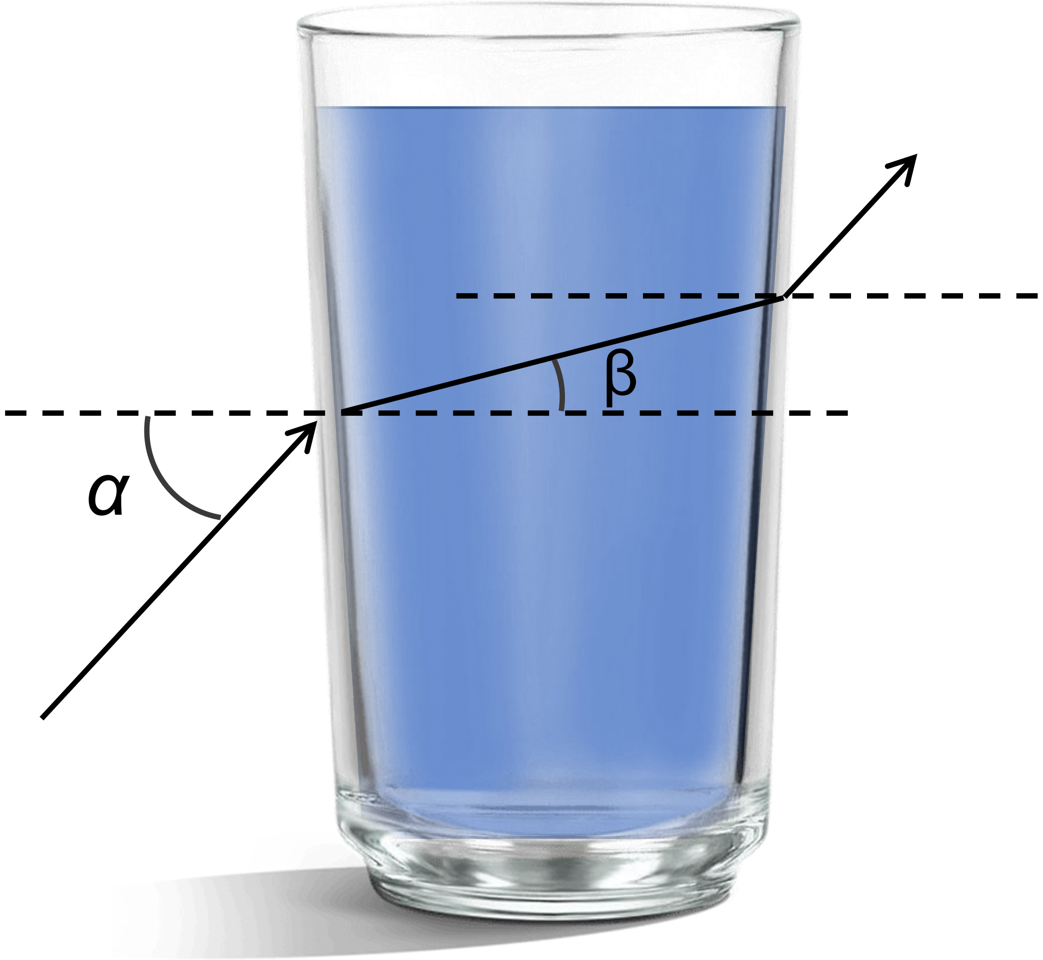
Attenuation factor

Attenuation Factor

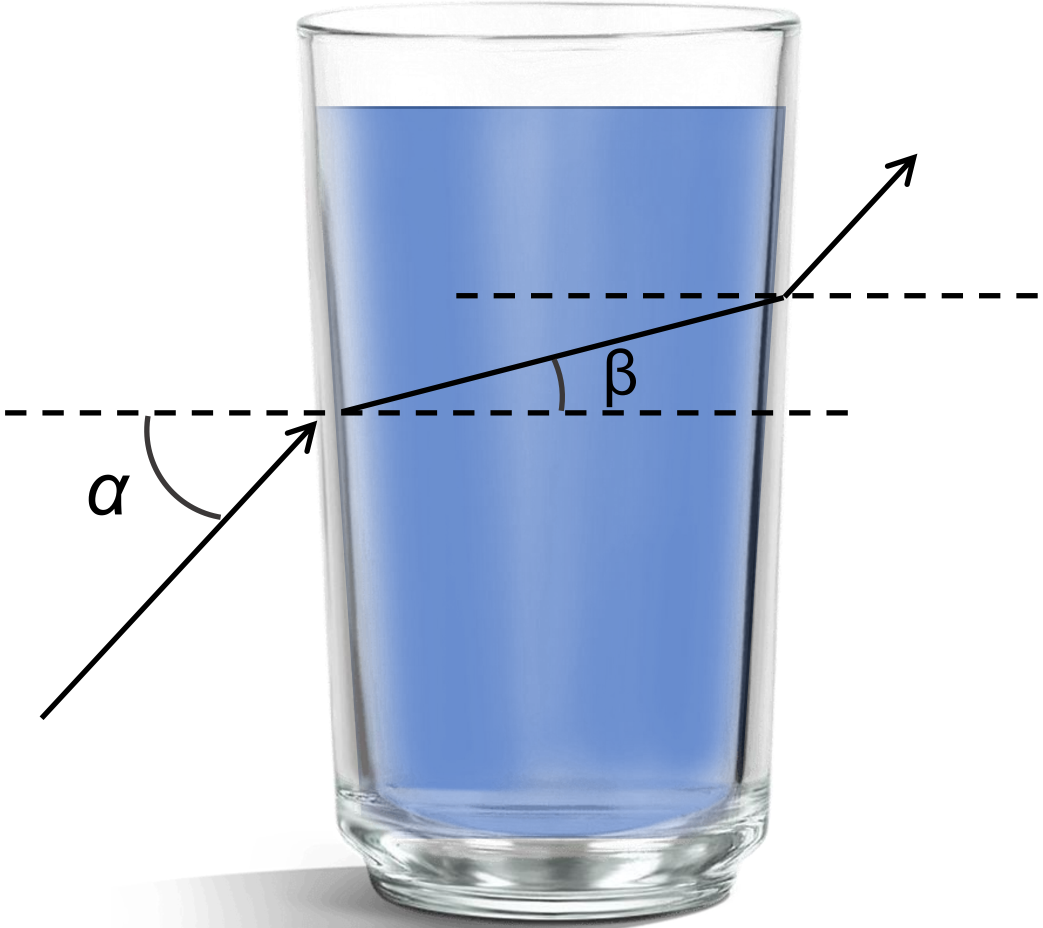


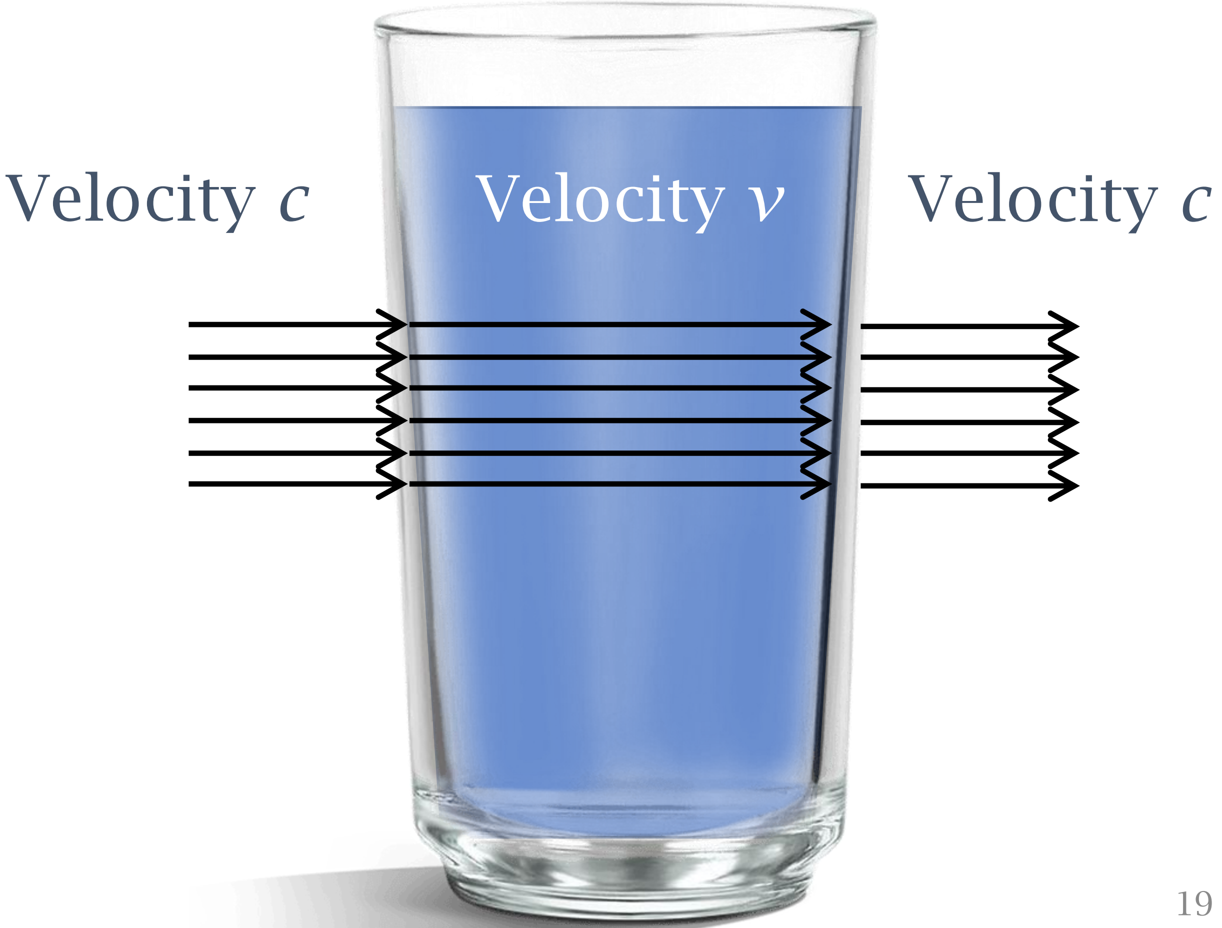
Reduced
signal strength

$$\text{Refractive Index} = \frac{\sin\alpha}{\sin\beta}$$

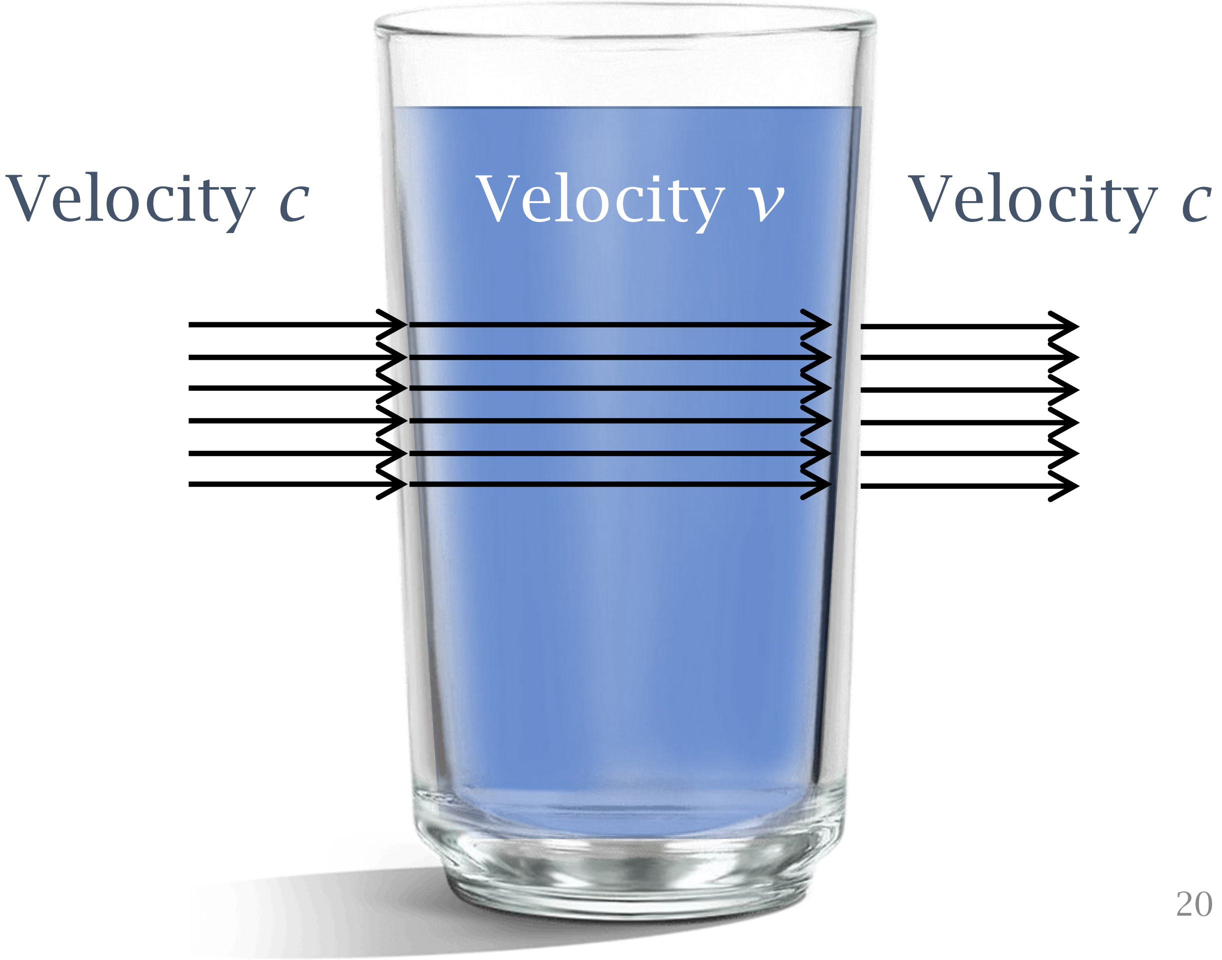


$$\text{Refractive Index} = \frac{\sin\alpha}{\sin\beta} = \frac{c}{v}$$



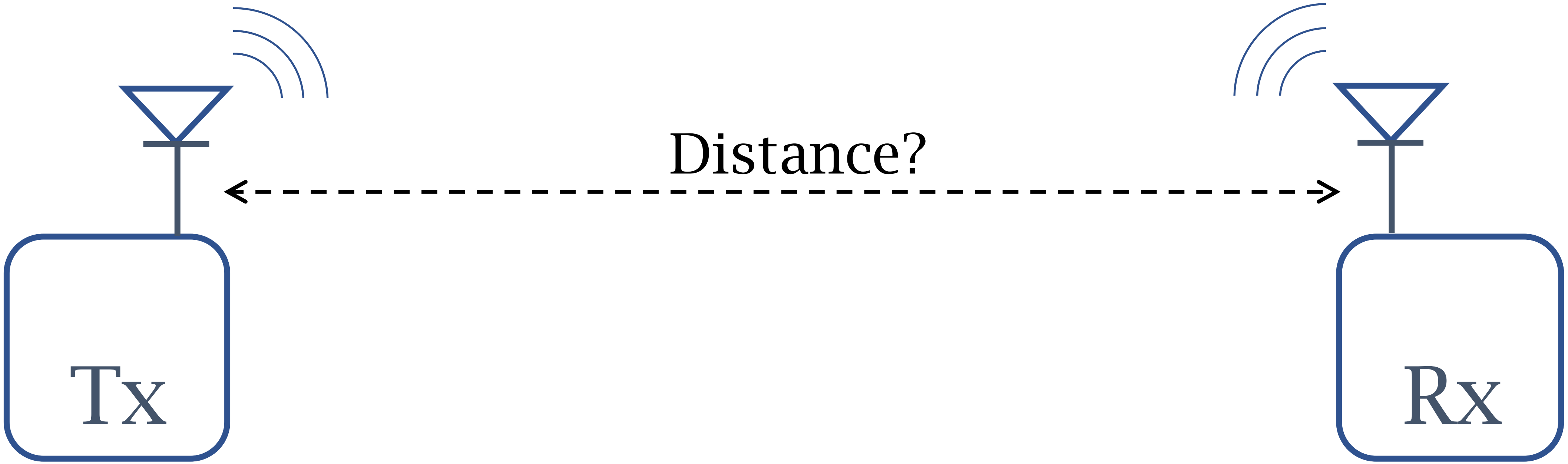


Refractive Index $= \frac{\sin\alpha}{\sin\beta} = \frac{c}{v}$

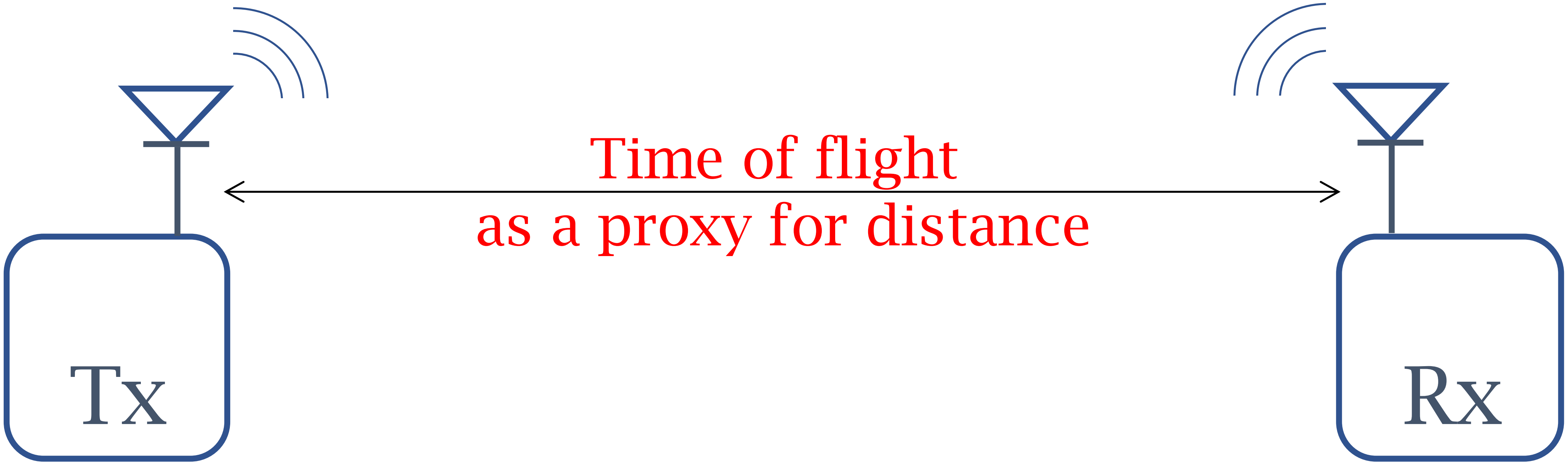


How to measure the slowdown?

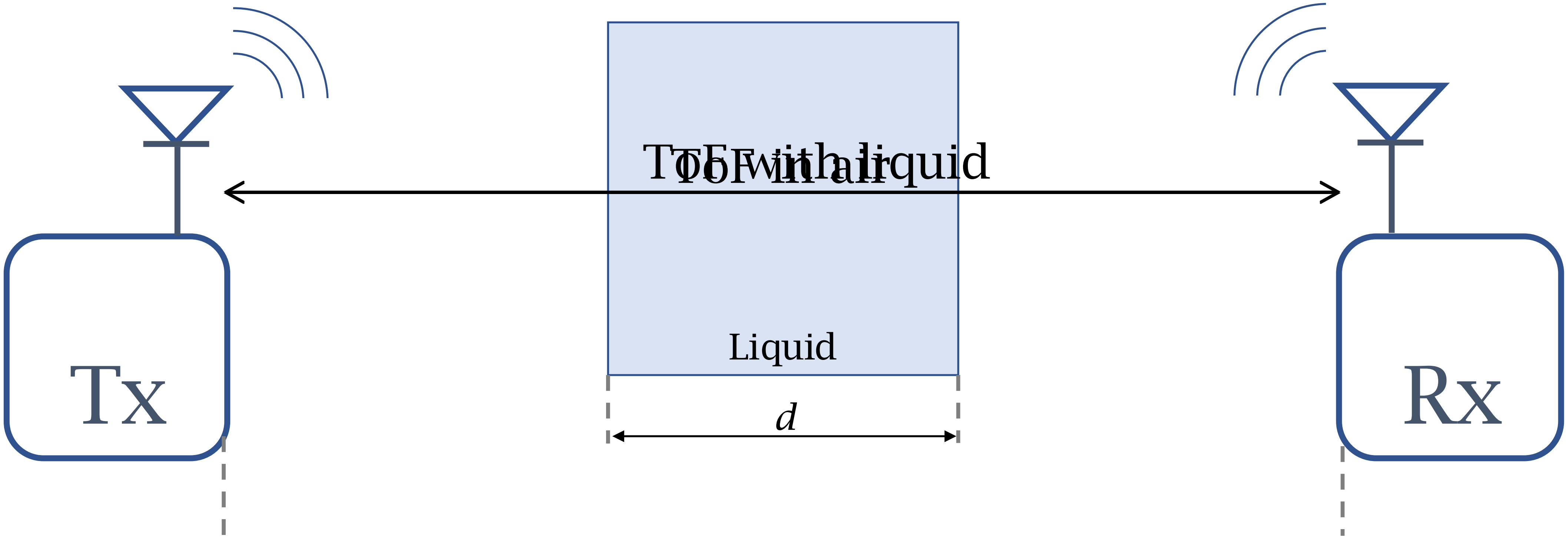
Wireless Localization



Time of Flight



Time of Flight



ToF gives Refractive Index

$$Refractive\ Index = \frac{c}{v}$$

Current State-of-the-art

- Ultra-wideband Radios
  - Inexpensive
  - 1GHz of bandwidth
  - ToF measurements at *1ns* granularity

Is this good enough?

State-of-the-art is insufficient

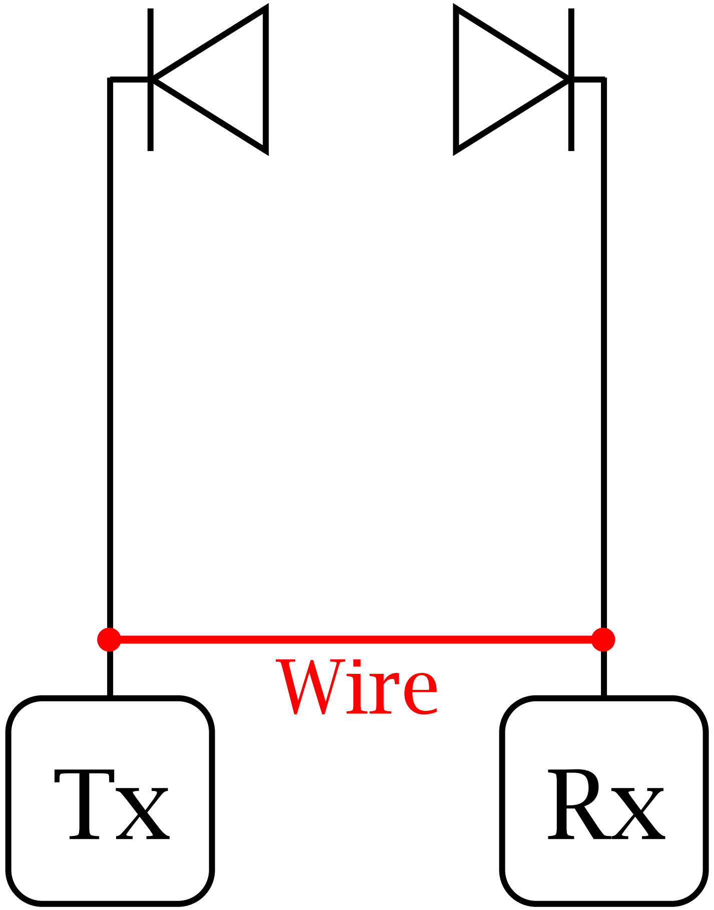
−

≈10 *picoseconds*

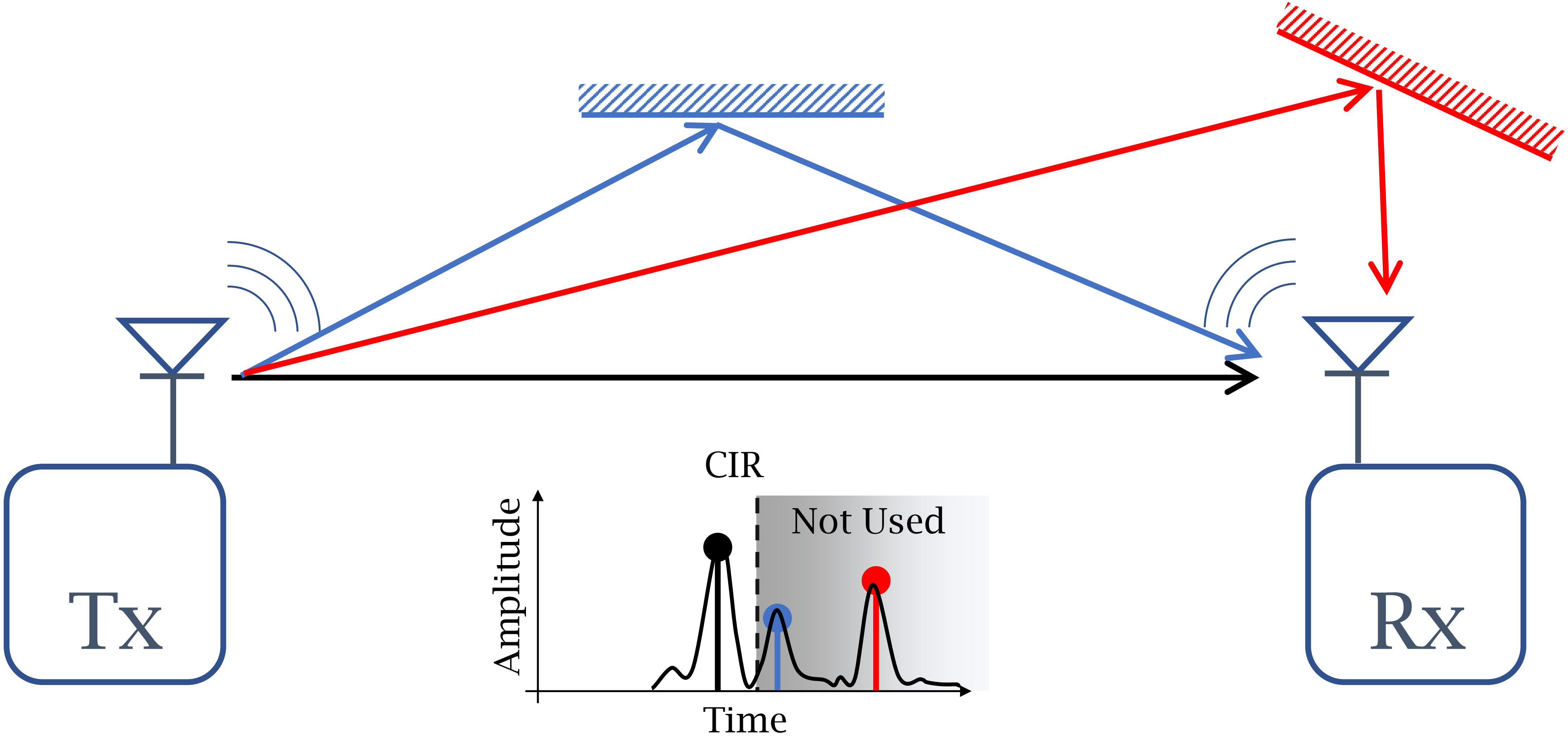
Soybean Oil?

Challenge: Measuring ToF at picoseconds granularity

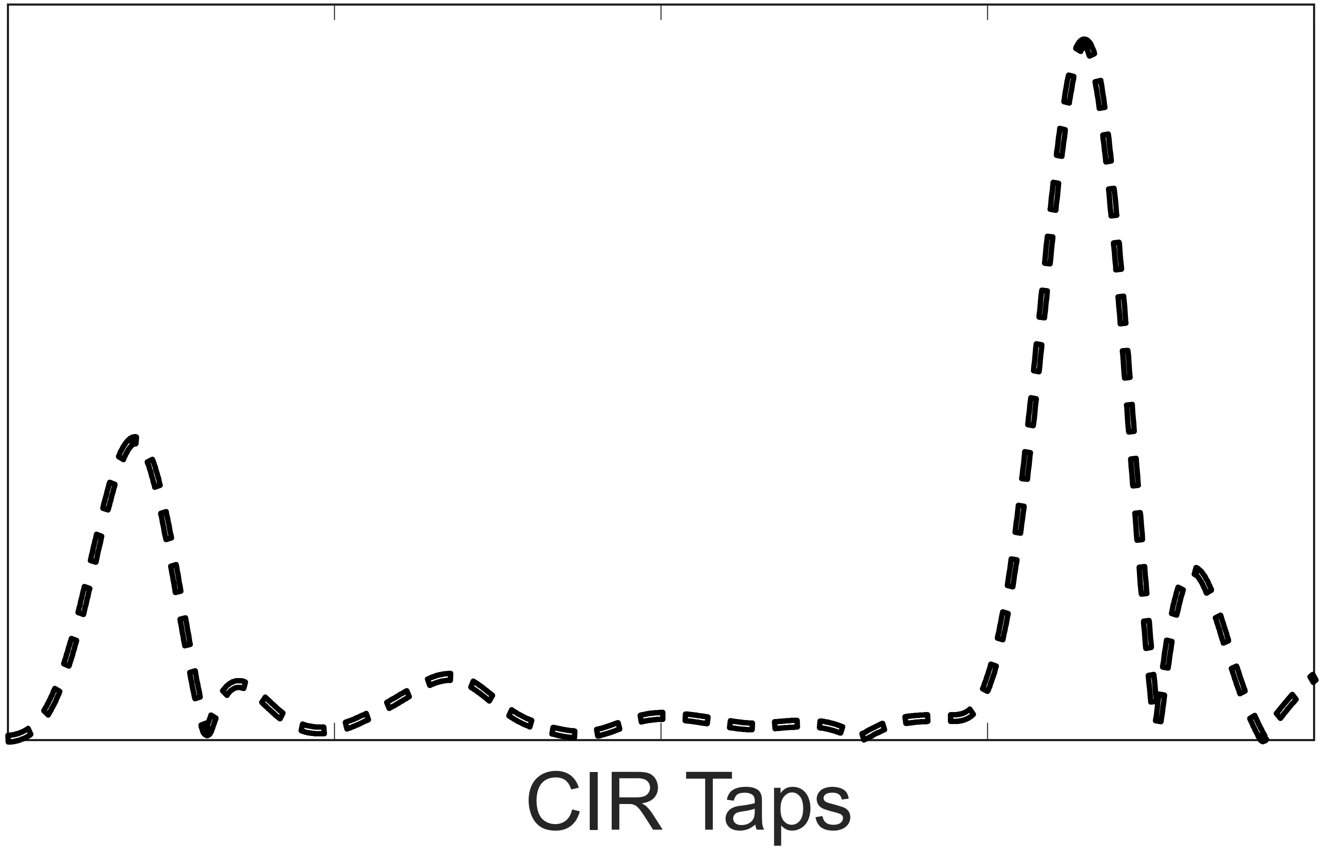
Our Contributions

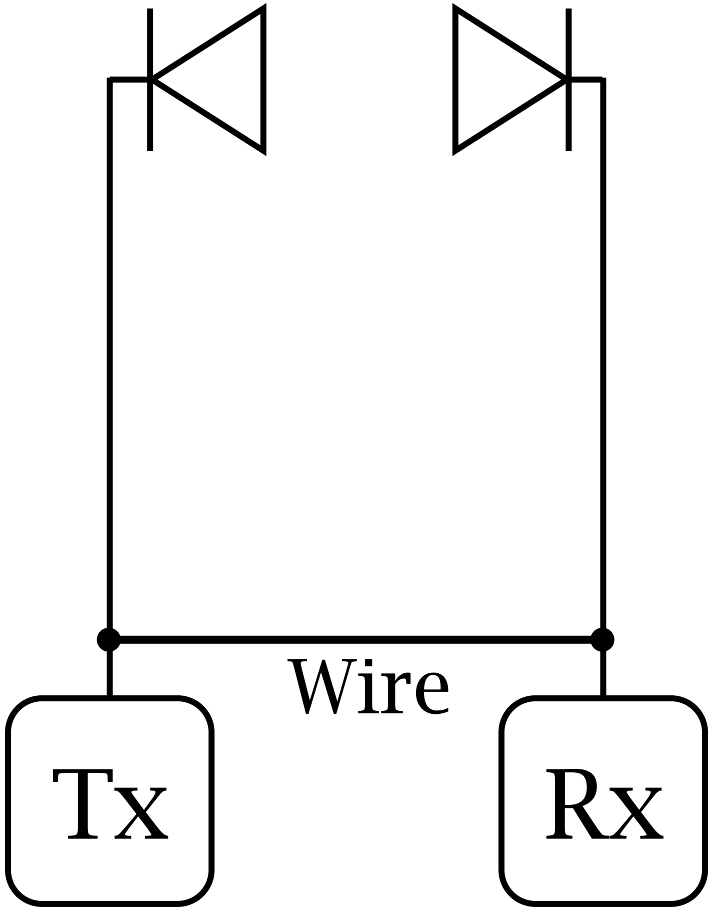


Channel Impulse Response

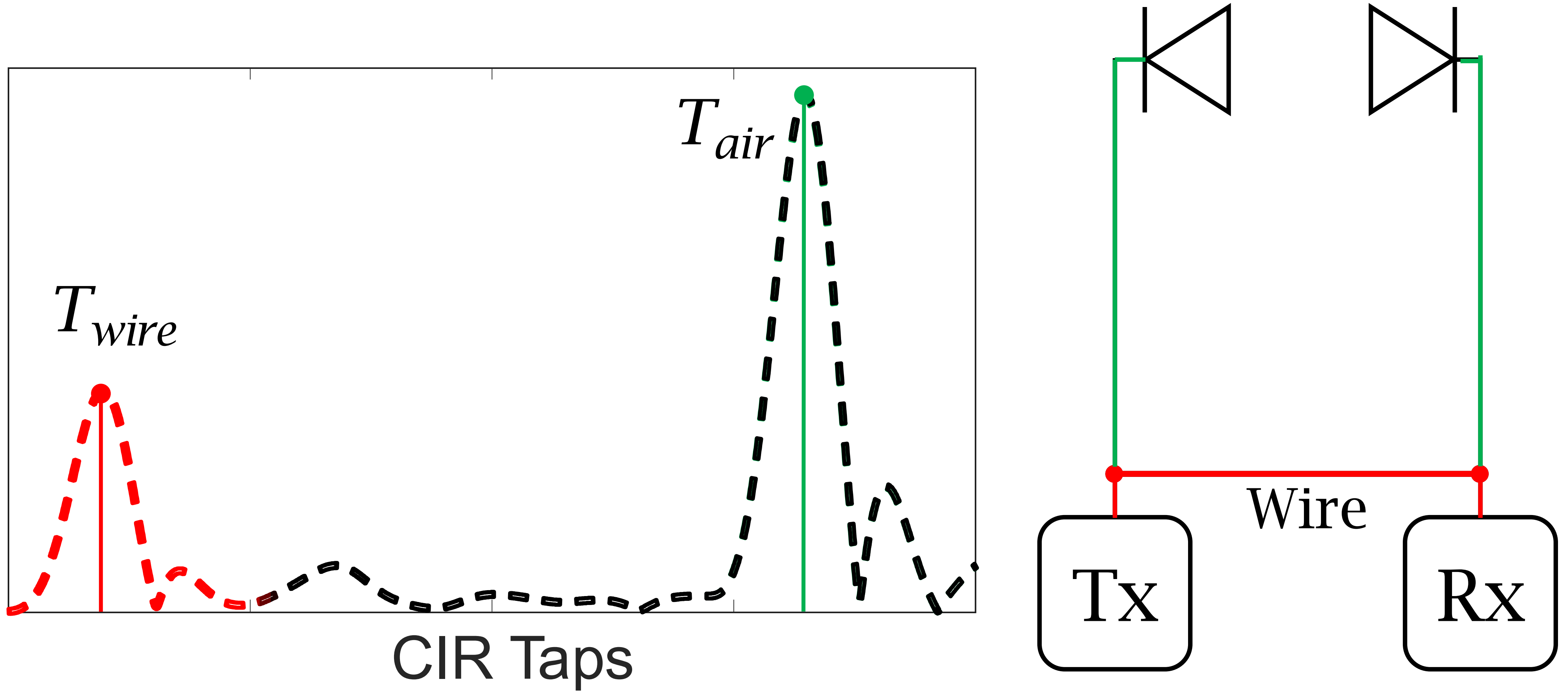


Channel Impulse Response

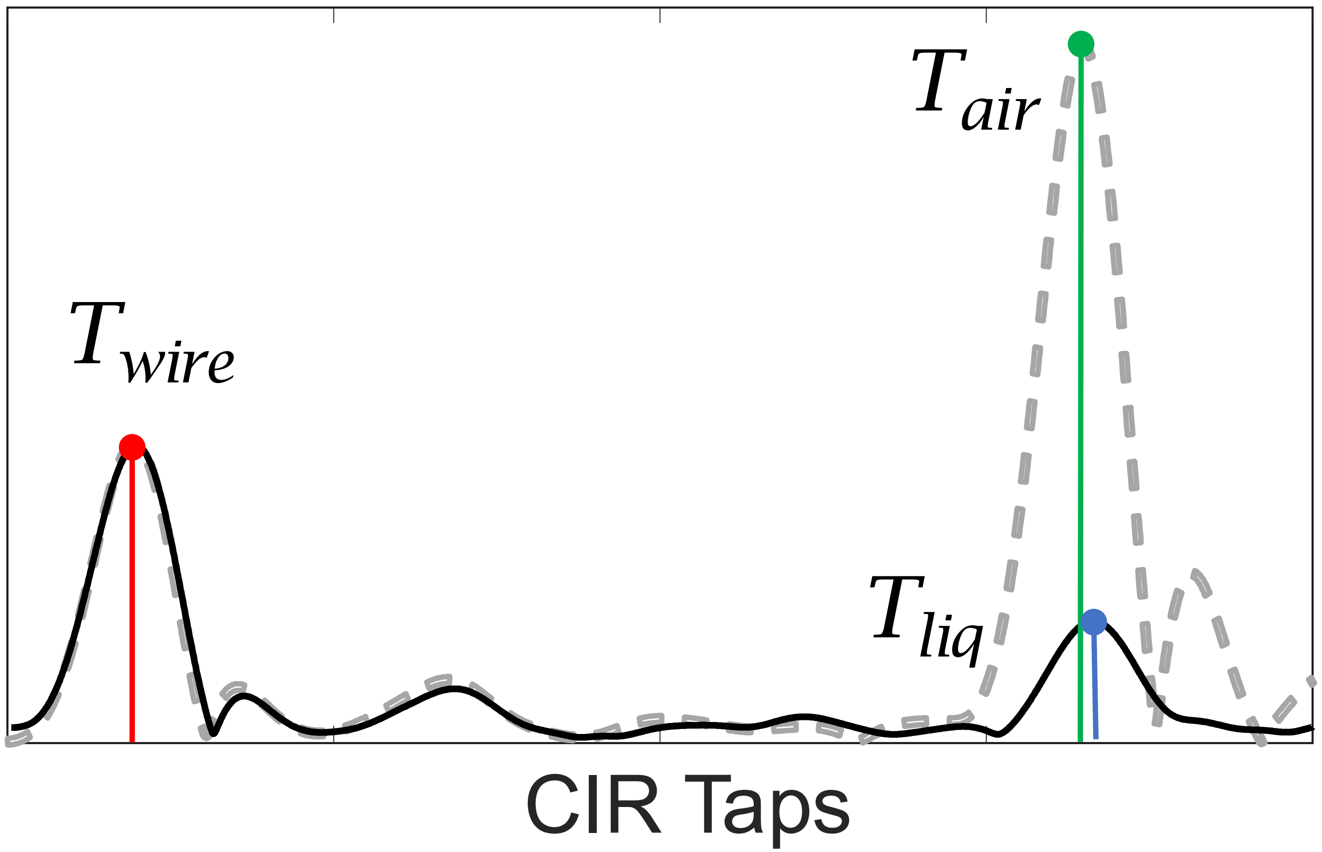


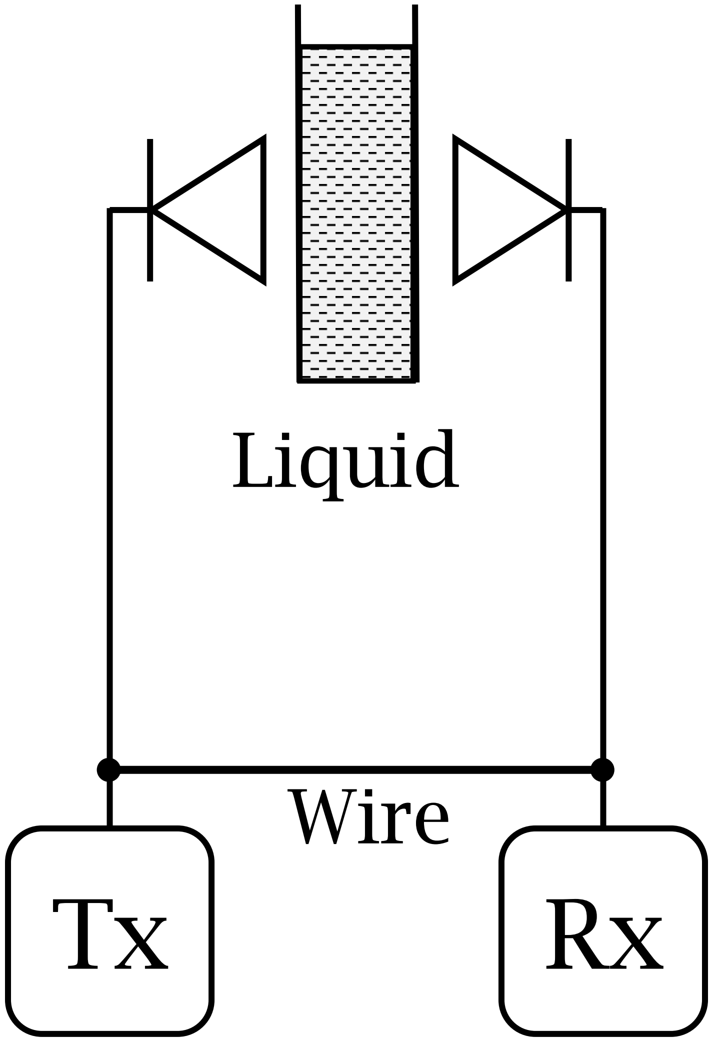


Channel Impulse Response

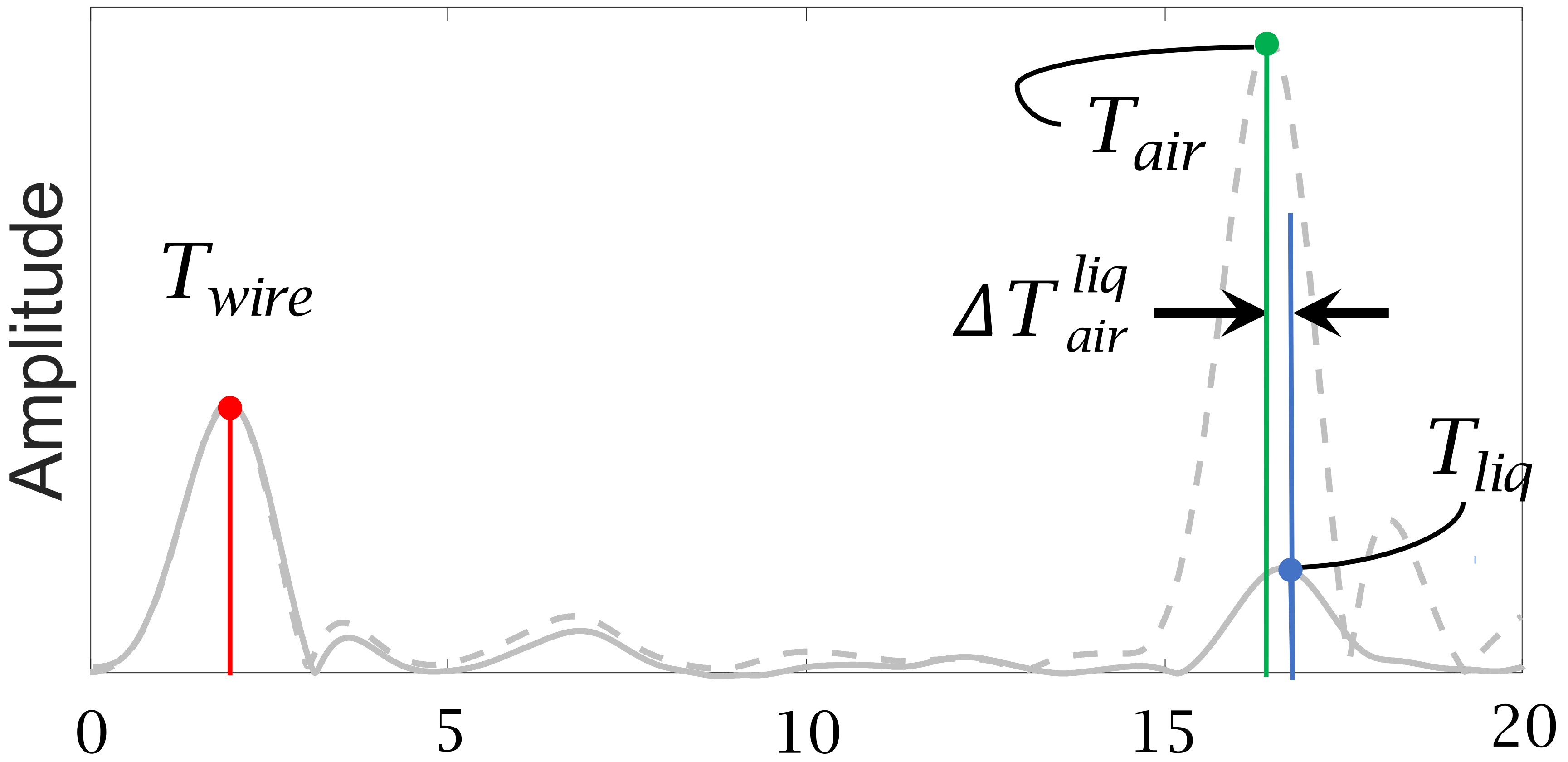


CIR with Liquid



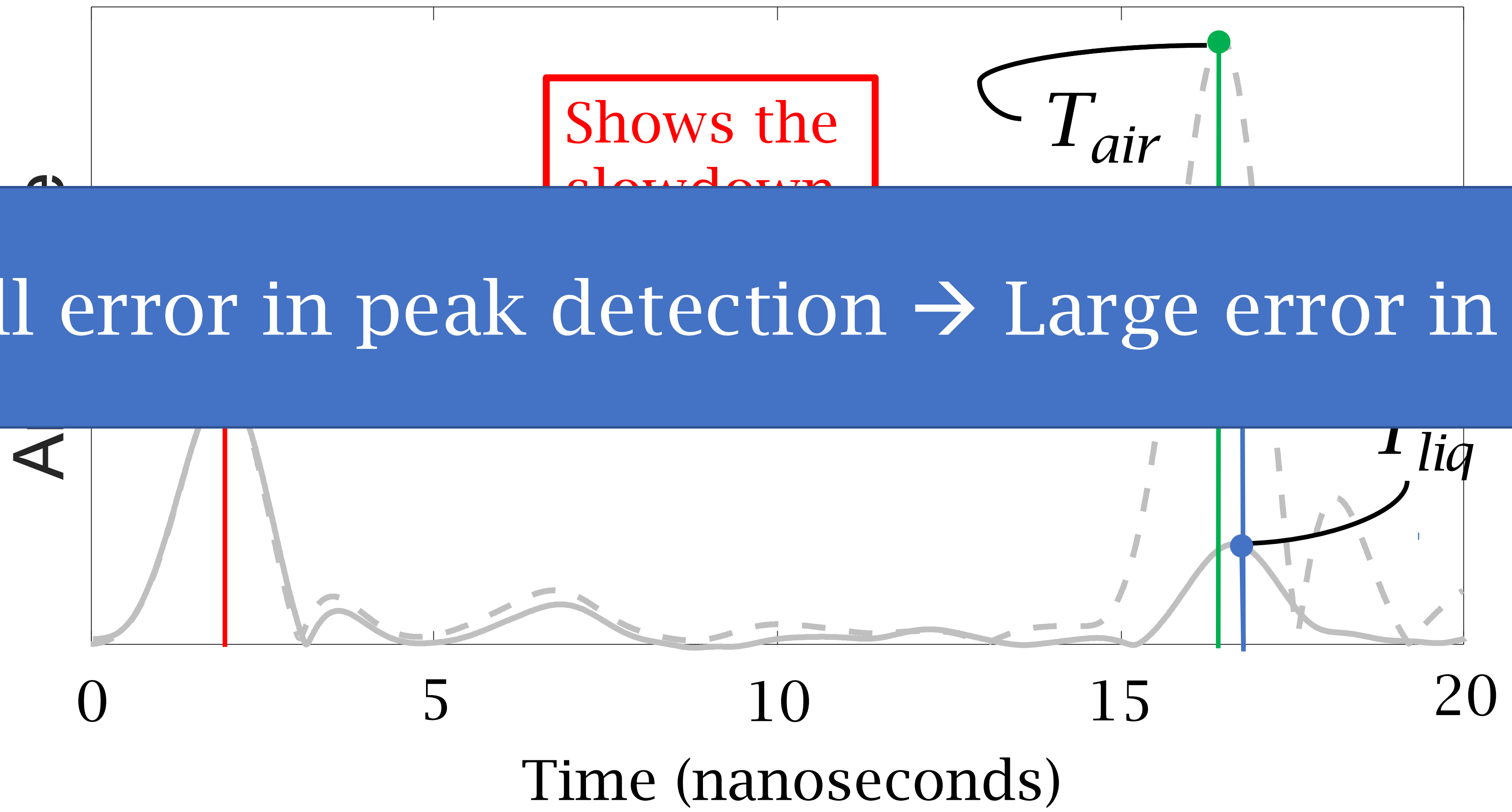


Double Differencing – Relative ToF



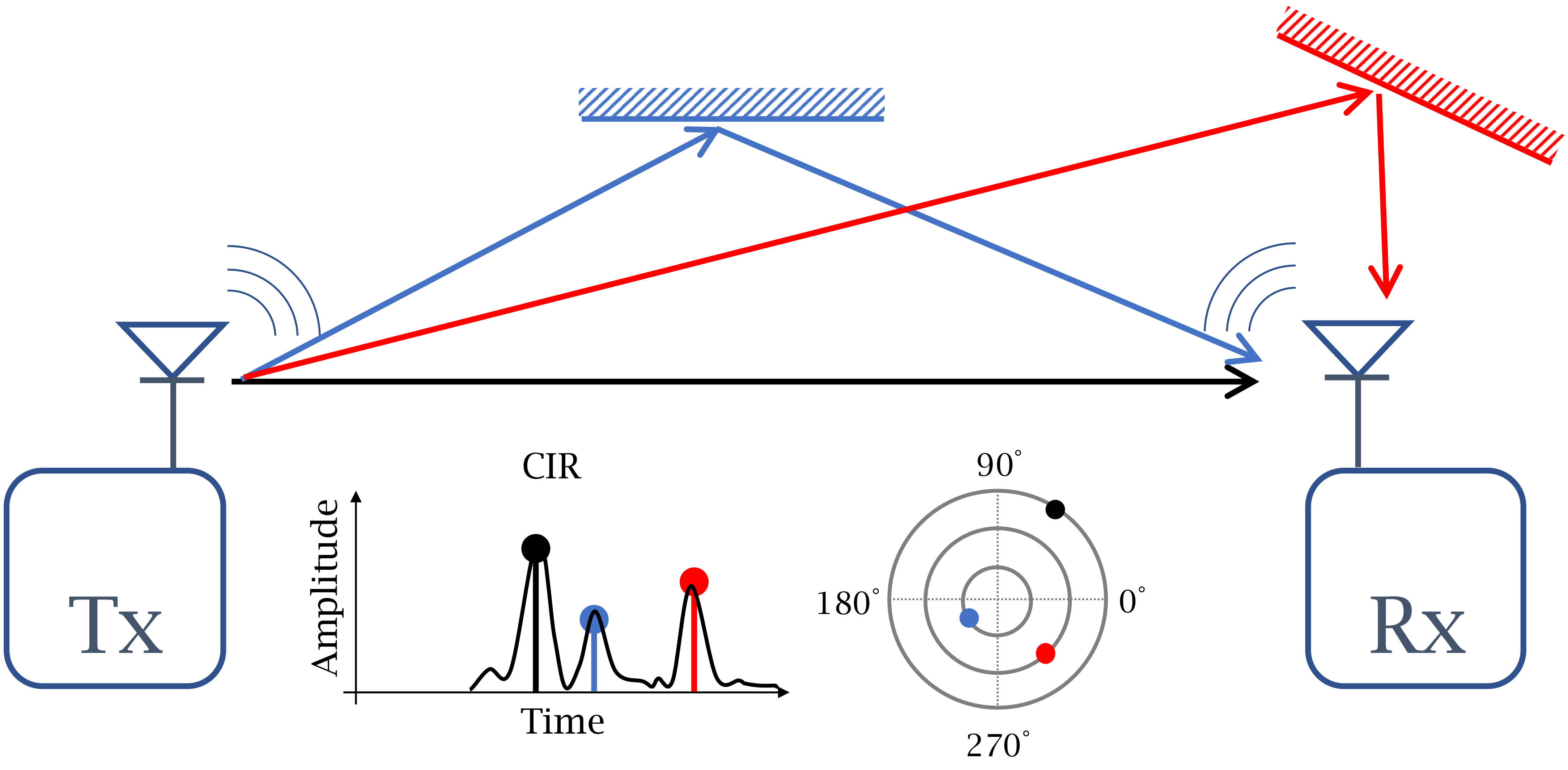
$$\Delta T_{air}^{liq} = (T_{liq} - T_{wire}) - (T_{air} - T_{wire})$$

Double Differencing – Relative ToF

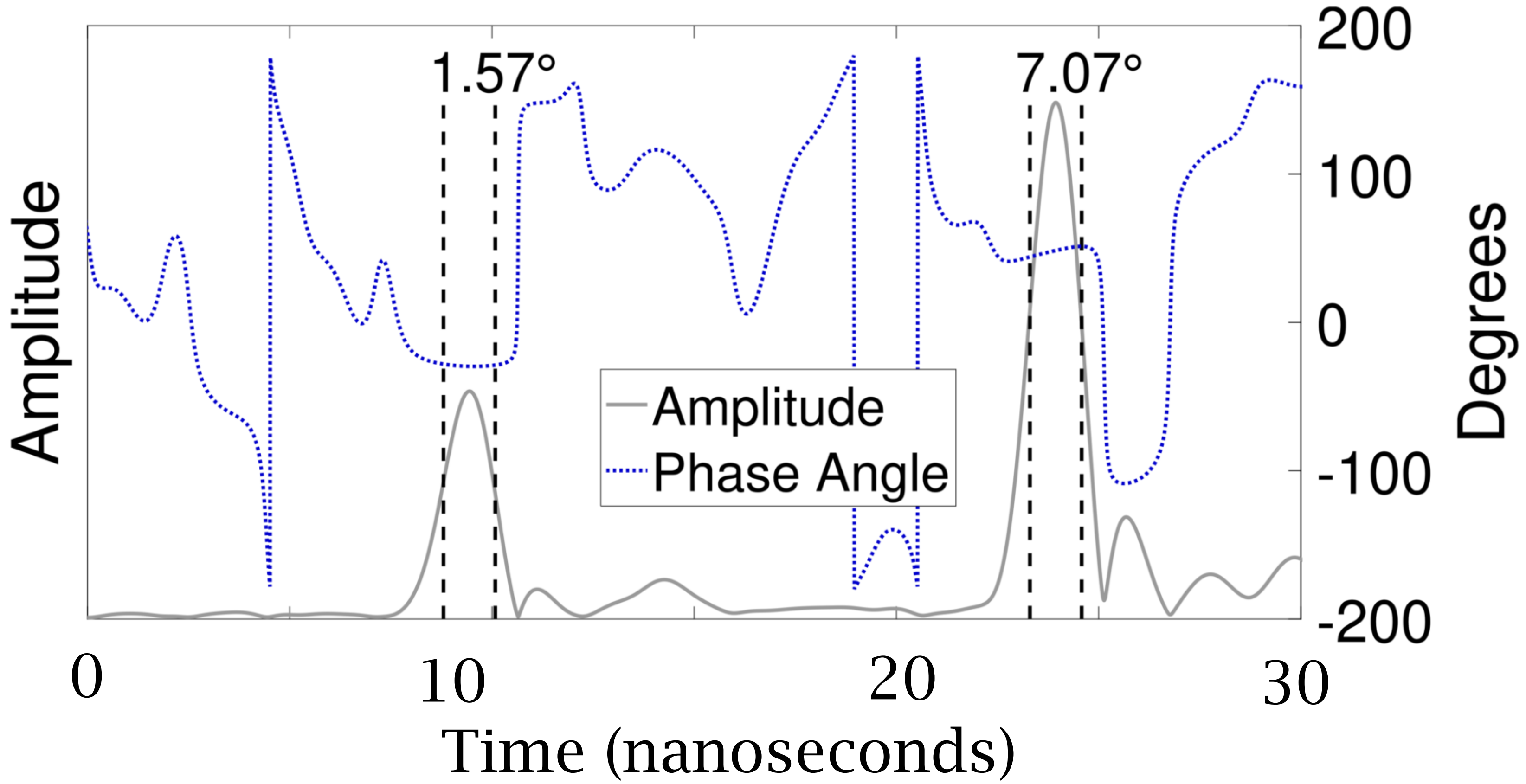


Small error in peak detection → Large error in ToF

CIR – Phase Information

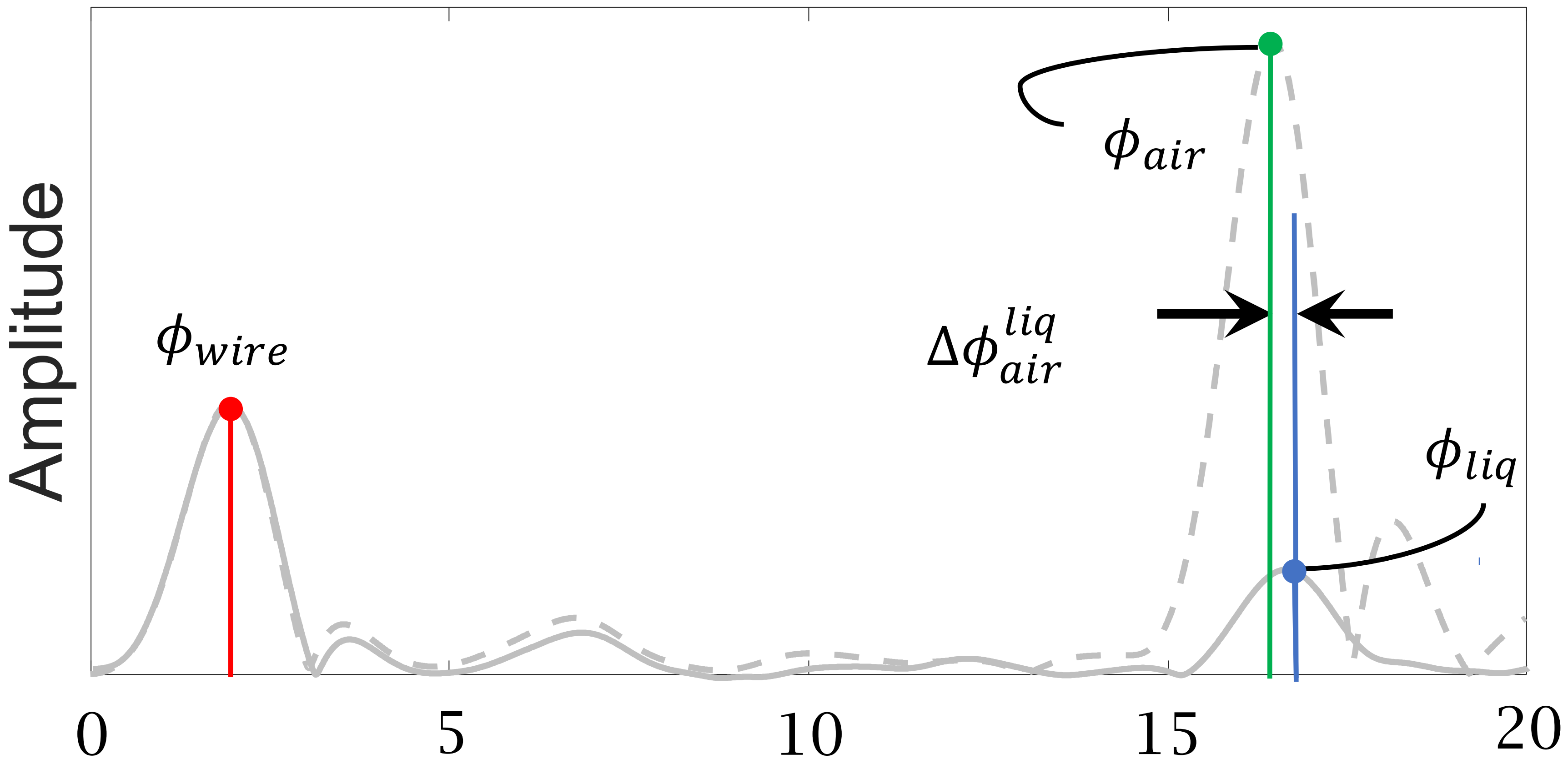


Phase to the rescue



Phase is more stable

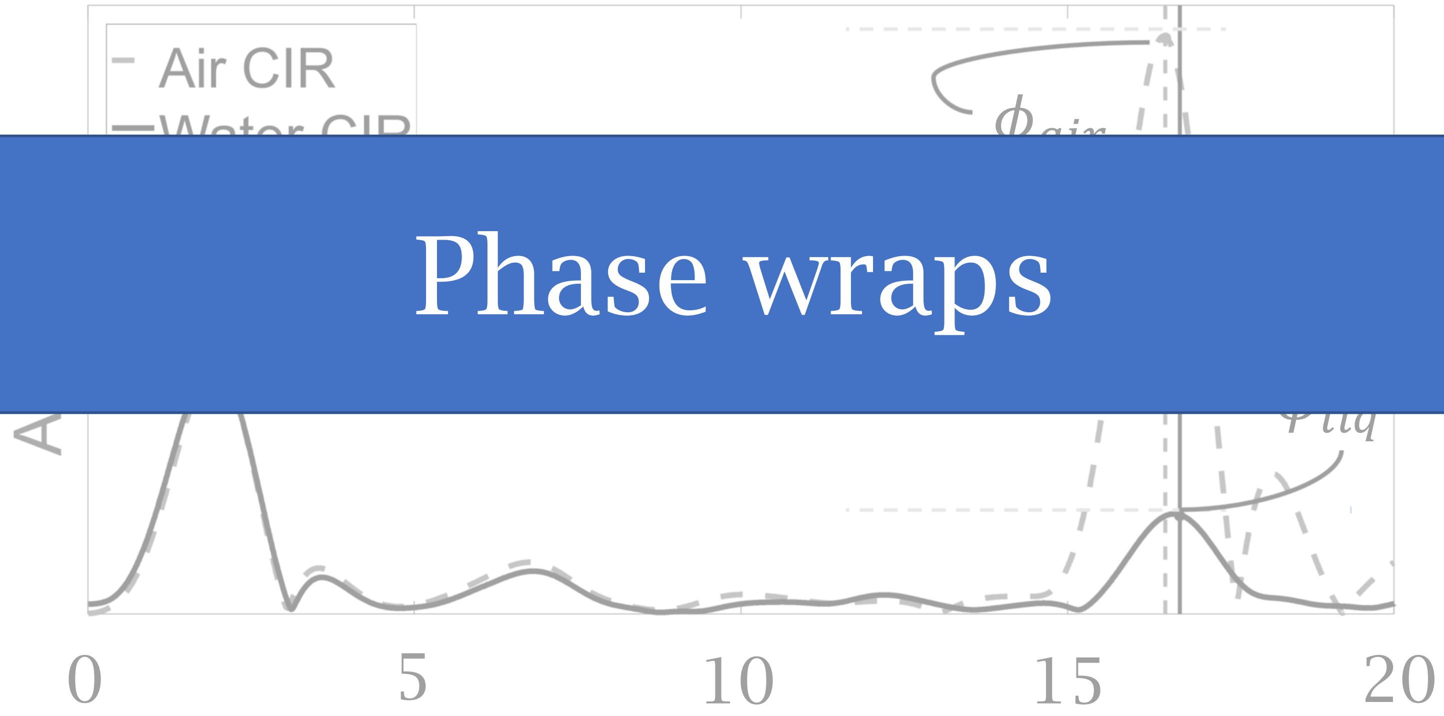
Double Differencing – Phase



$$\Delta\phi_{air}^{liq} = (\phi_{liq} - \phi_{wire}) - (\phi_{air} - \phi_{wire})$$

Double Differencing – Phase

- Phase ϕ can be arbitrary, but difference is meaningful

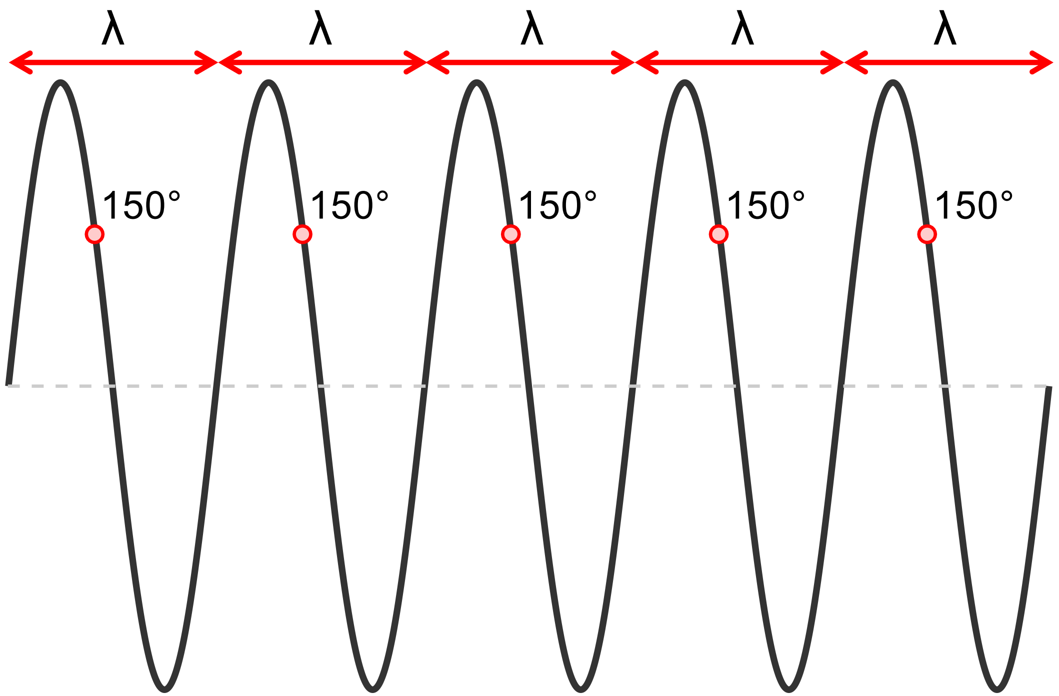


Phase wraps

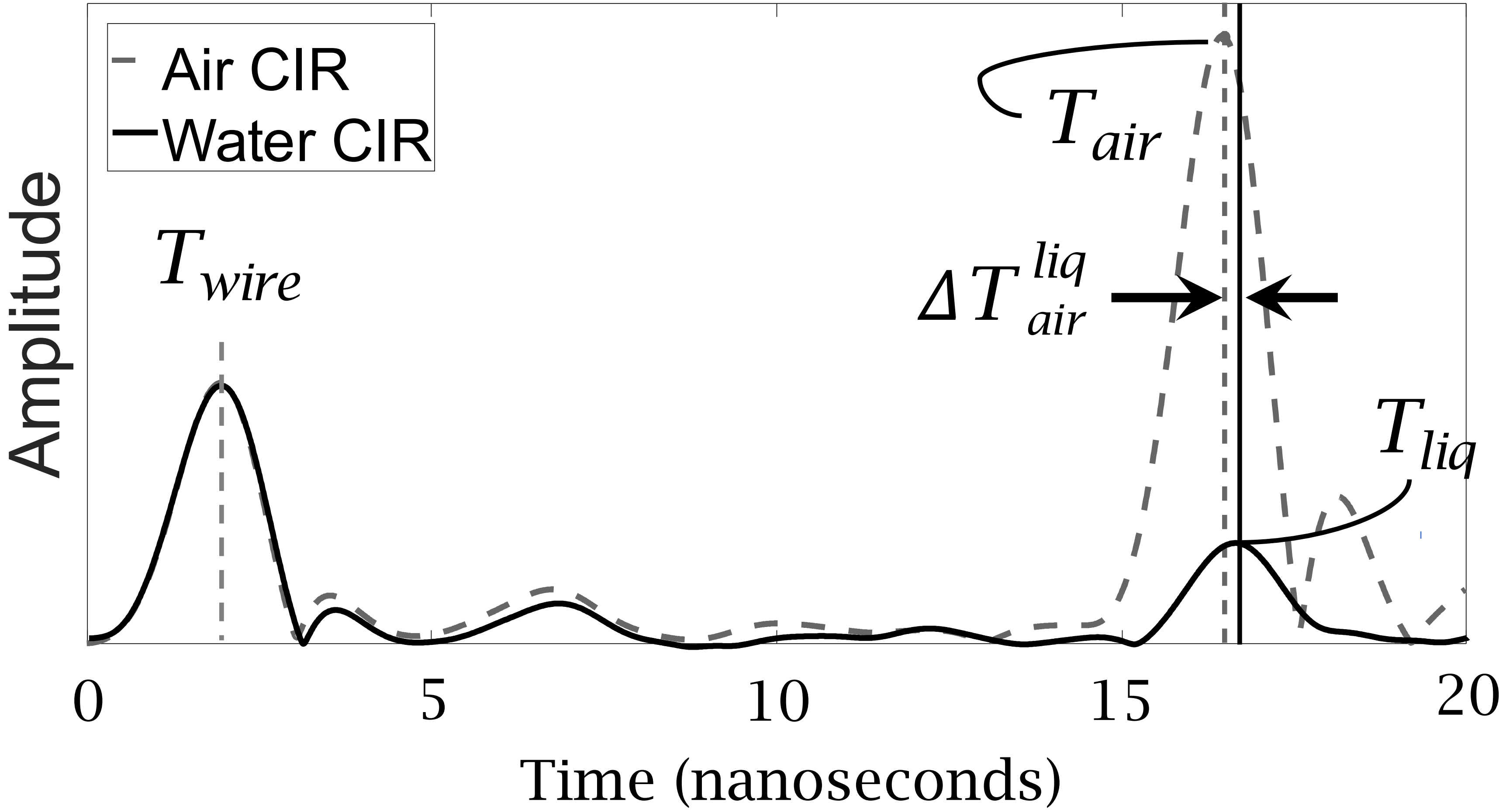
$$\Delta\phi_{air}^{liq} = (\phi_{liq} - \phi_{wire}) - (\phi_{air} - \phi_{wire})$$

Phase Wraps

- Using just phase is ambiguous
- Need some notion of absolute distance

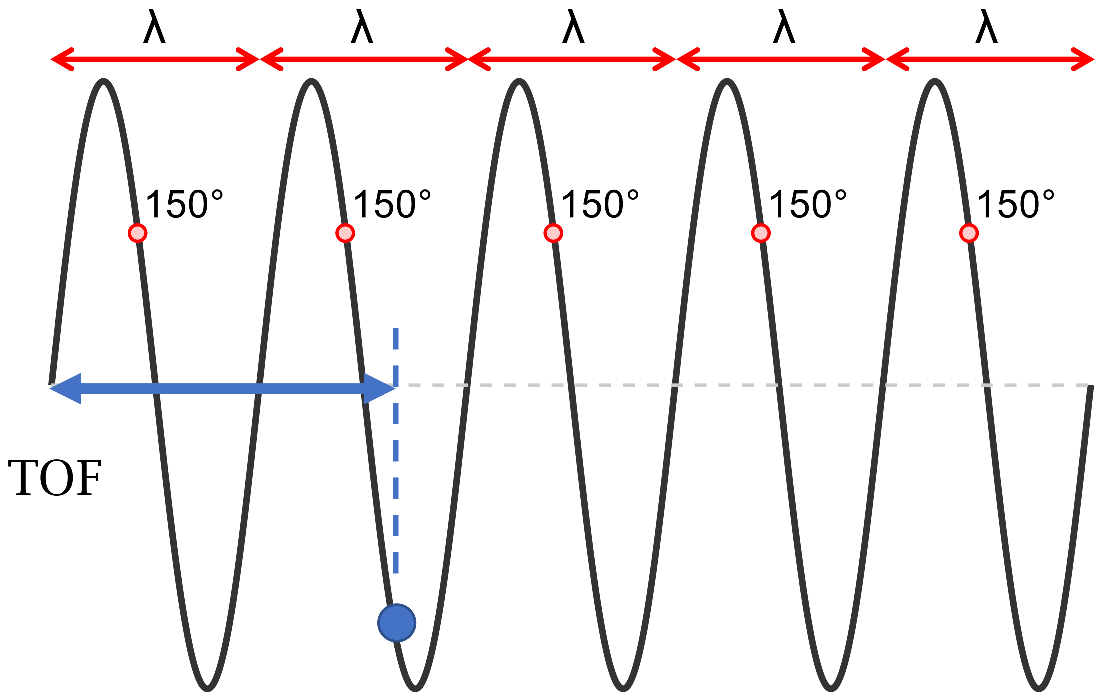


Double Differencing –ToF



Improvements using Phase

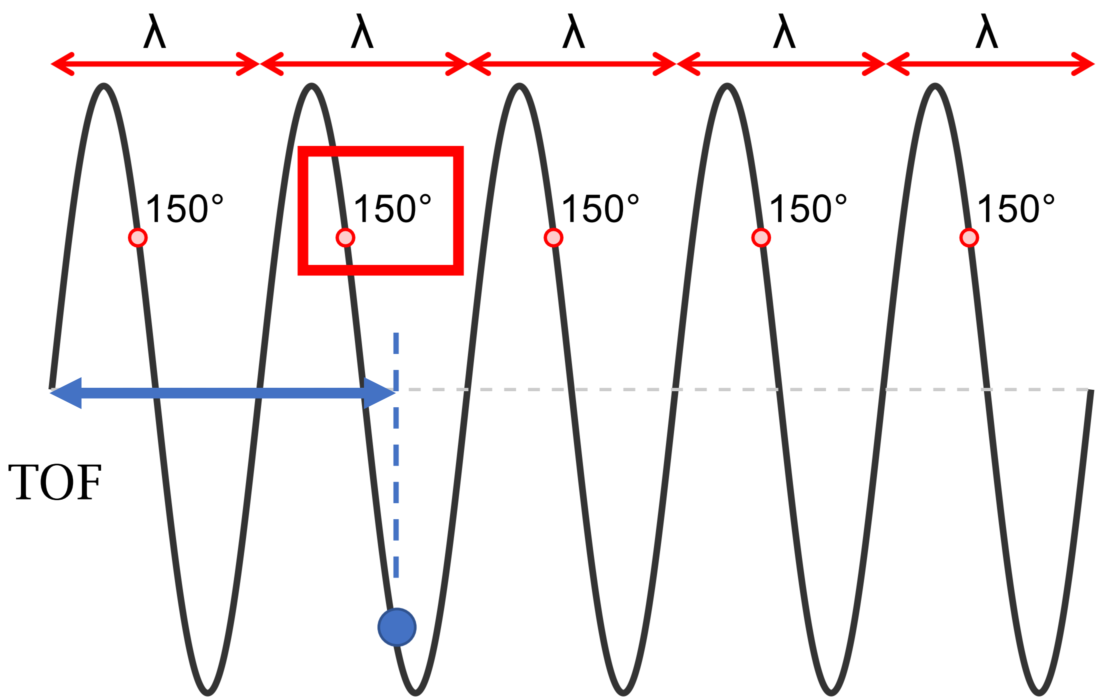
$$\Delta\phi_{air}^{liq} \neq \frac{\Delta T_{air}^{liq}}{wavelength} * 360$$



Improvements using Phase

$$\Delta T'^{liq}_{air} \approx n * (wavelength) + \Delta\phi^{liq}_{air}$$

$$n \in [0, 1, 2, \ldots]$$

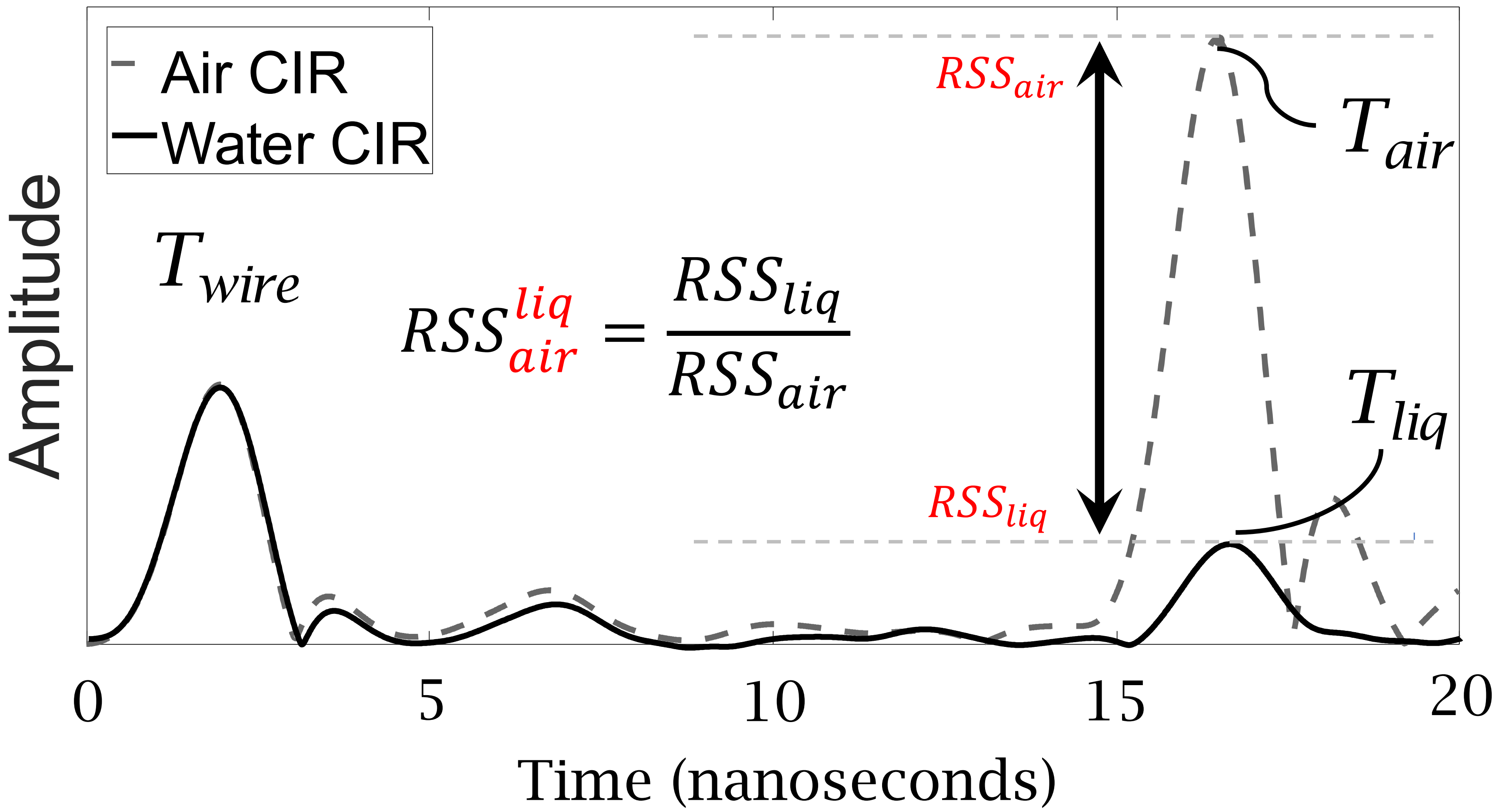


Key Properties of Liquids

✓ Refractive index

Attenuation factor

Estimating Attenuation



Key Properties of Liquids

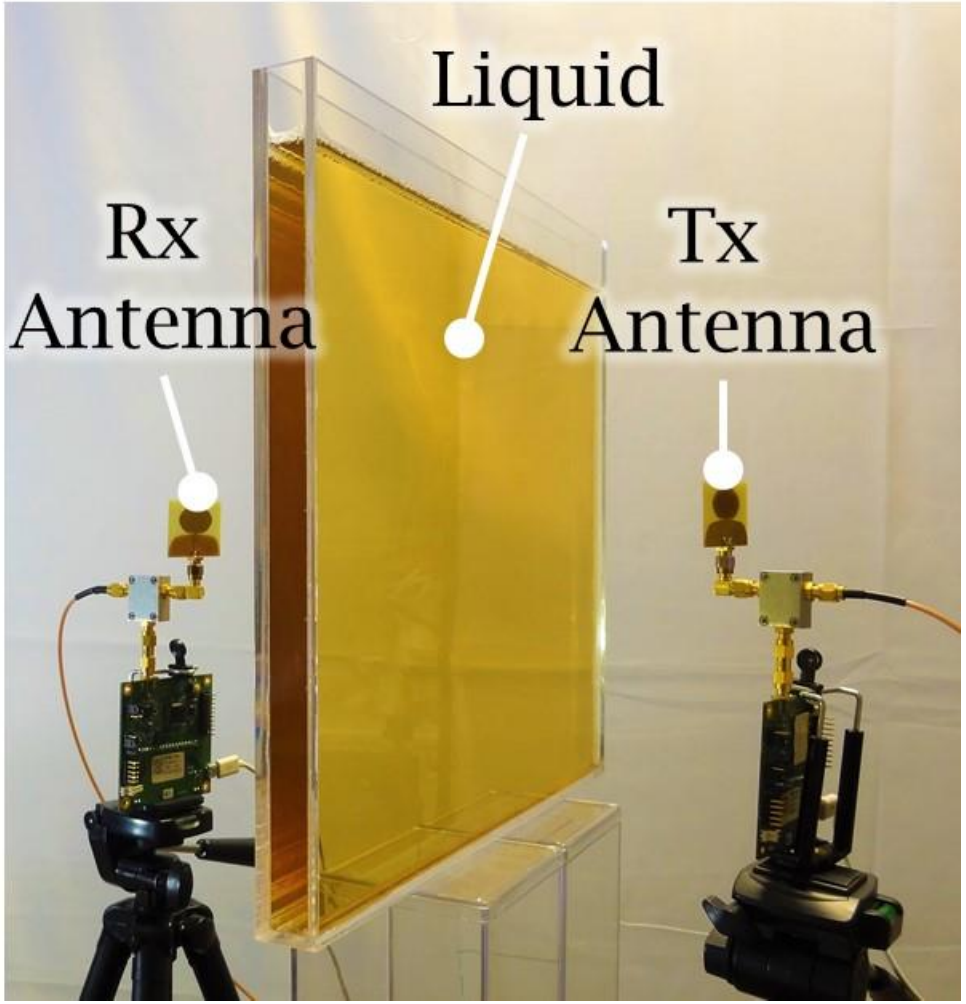
✓ Refractive index

✓ Attenuation factor

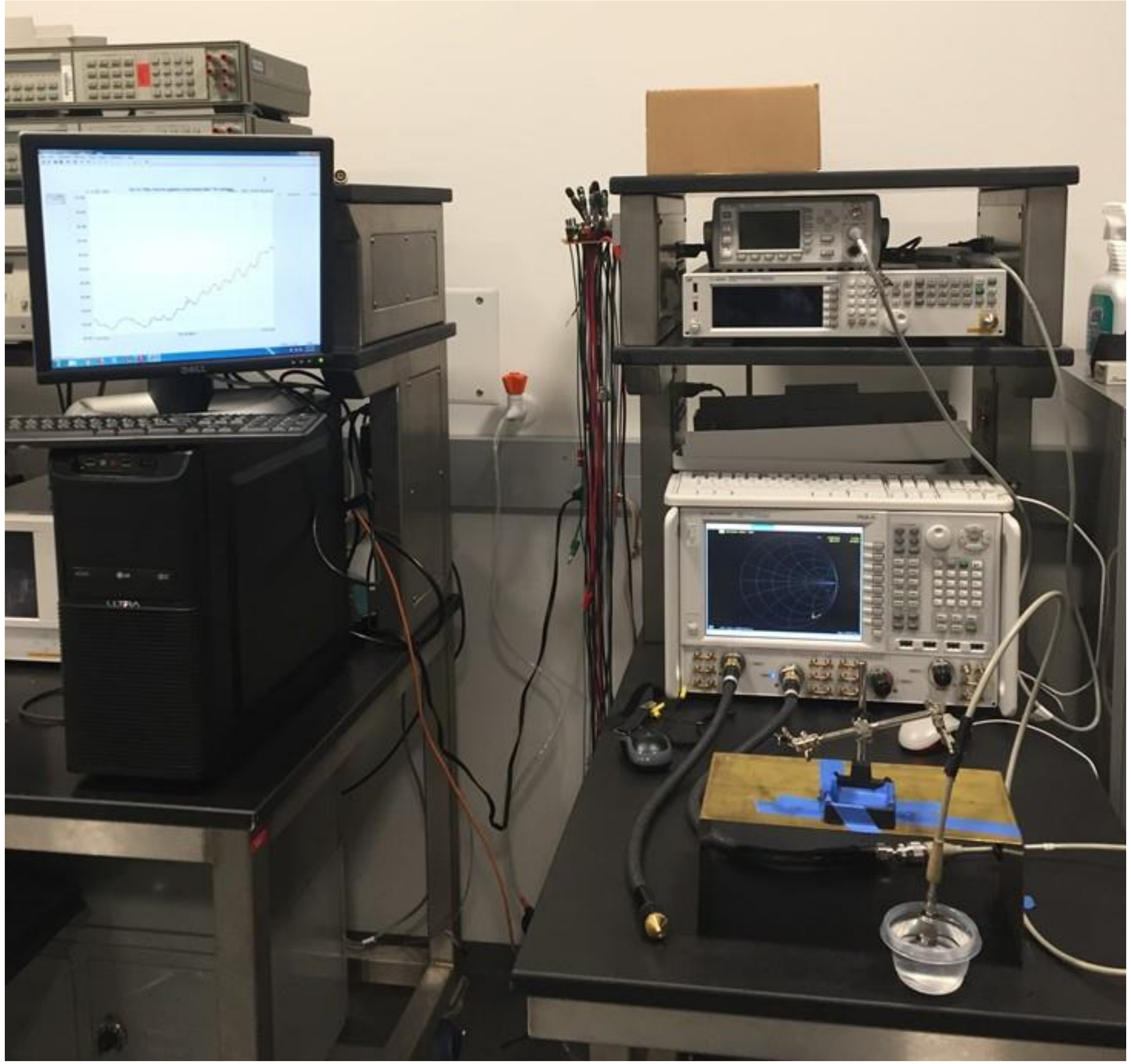
Results

Experimental Setup

- Used Decawave Trek 1000 UWB devices at 4GHz
- 38cm x 36cm liquid container
- 33 liquids spanning a large part of the refractive index spectrum

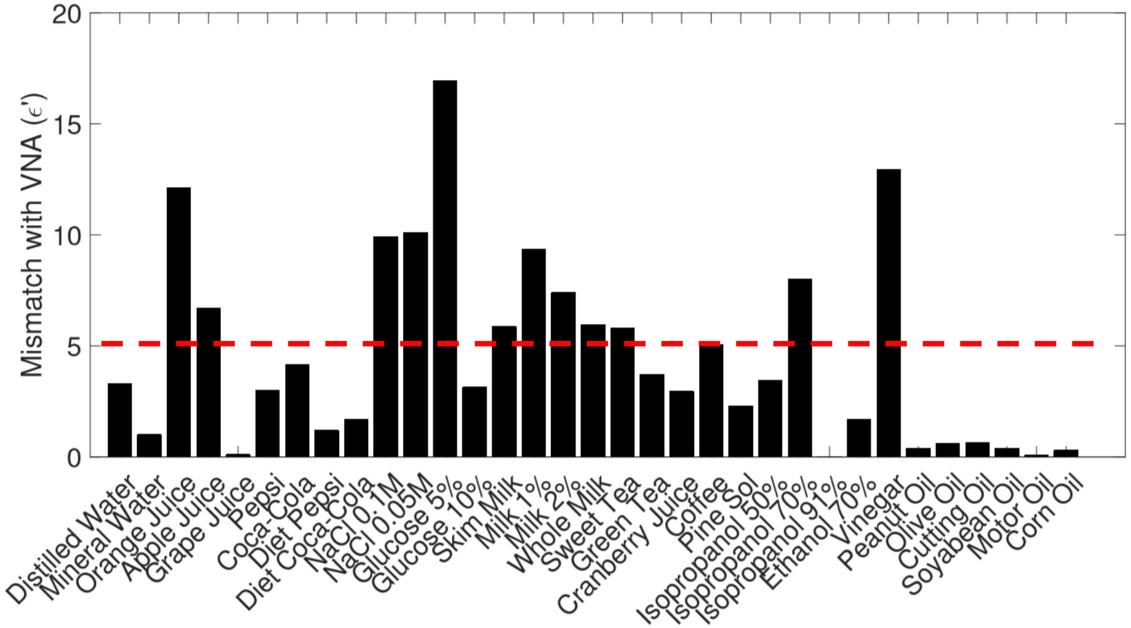


Baseline: Vector Network Analyzer



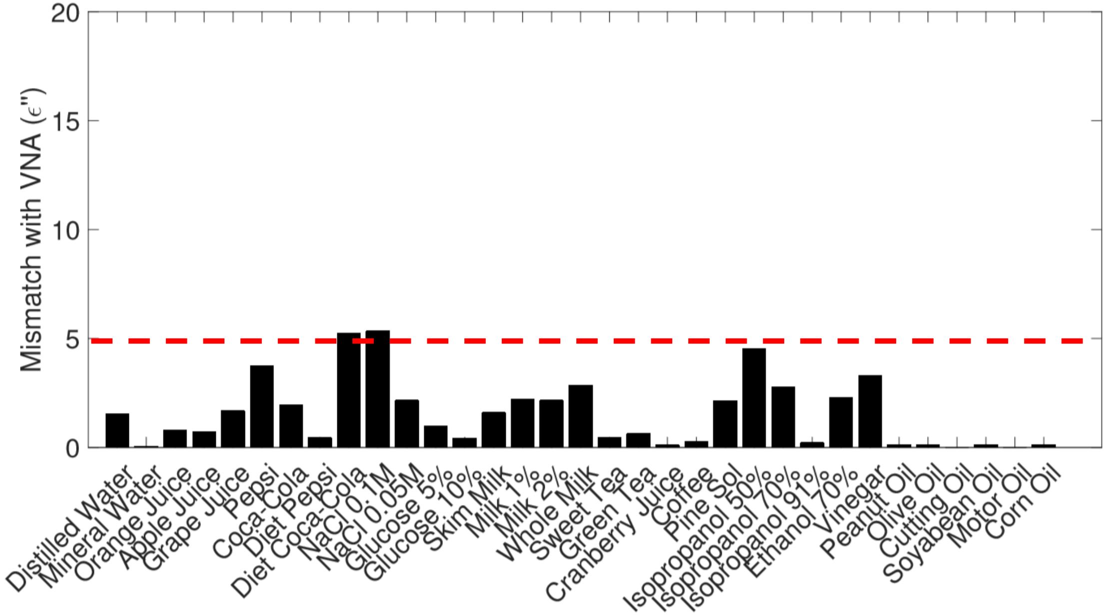
- VNA + Dielectric Probe method for creating a baseline
- Measures the liquid's complex permittivity
- Published error is 5%

Results – Permittivity

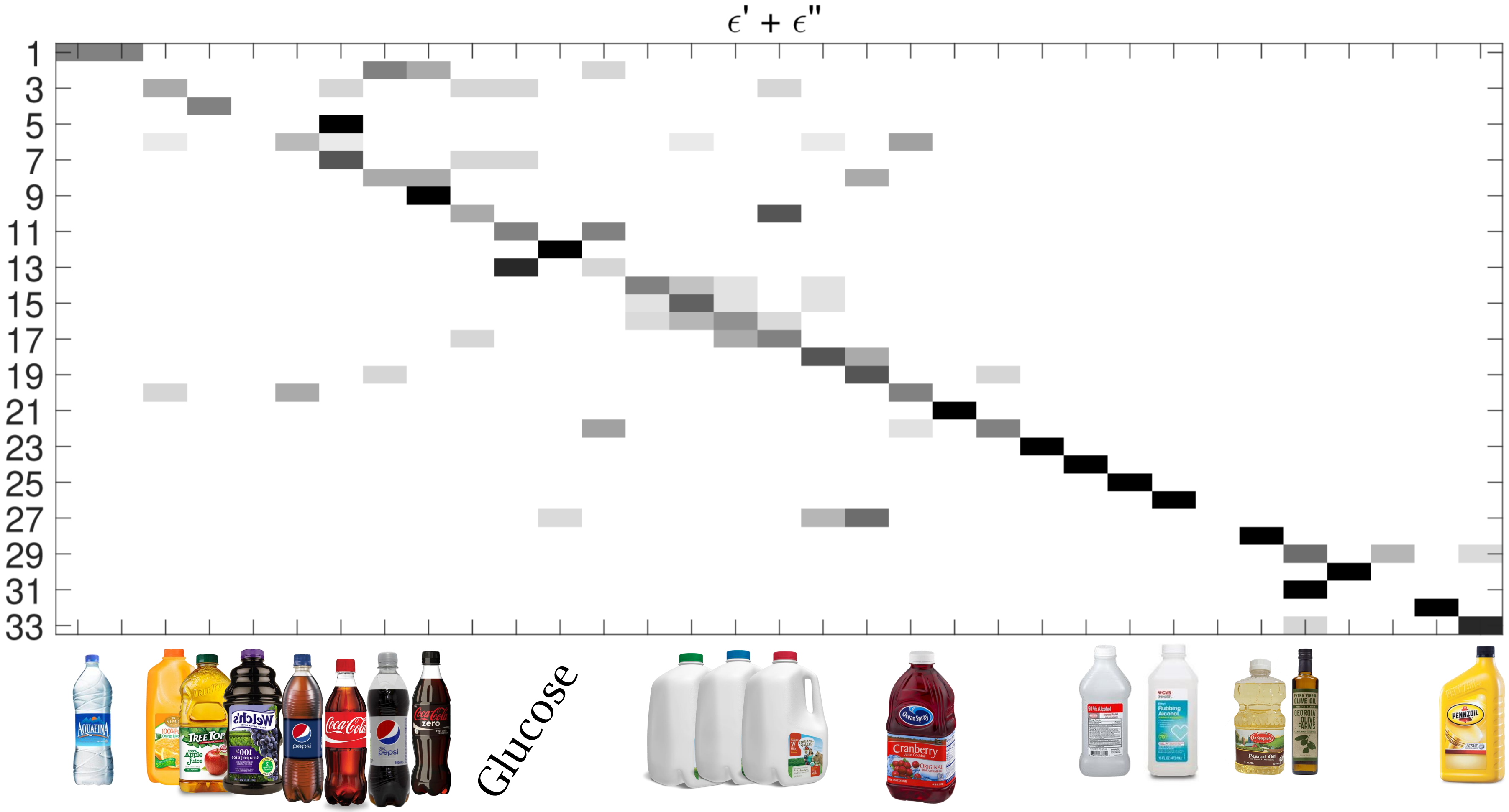


Median Error in ϵ' is under 9%

Median Error in ϵ'' is under 12%



Results – Identification

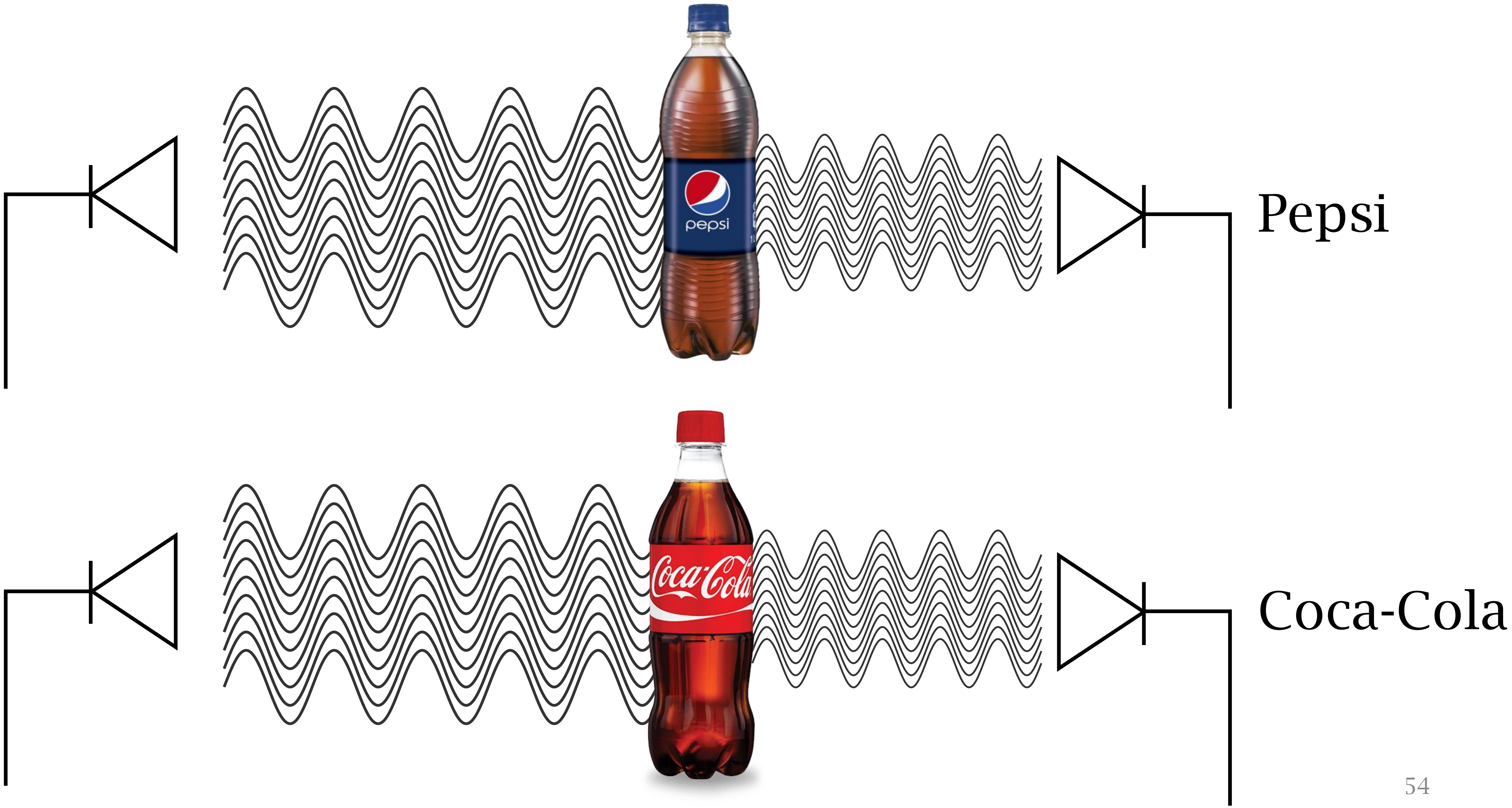


Limitations and Future work

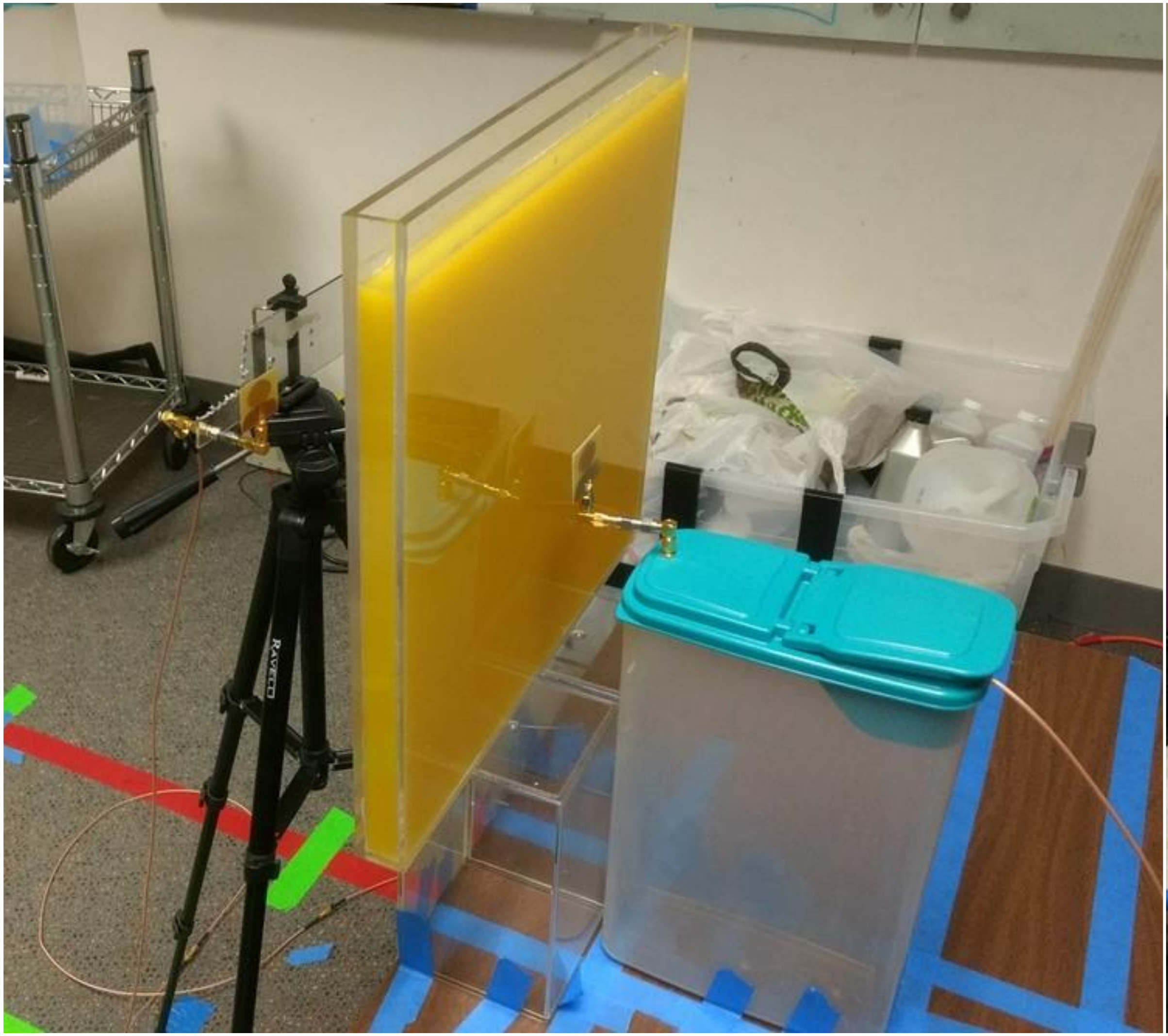
Composition of Mixtures

Container Shape

Conclusion



Thank You

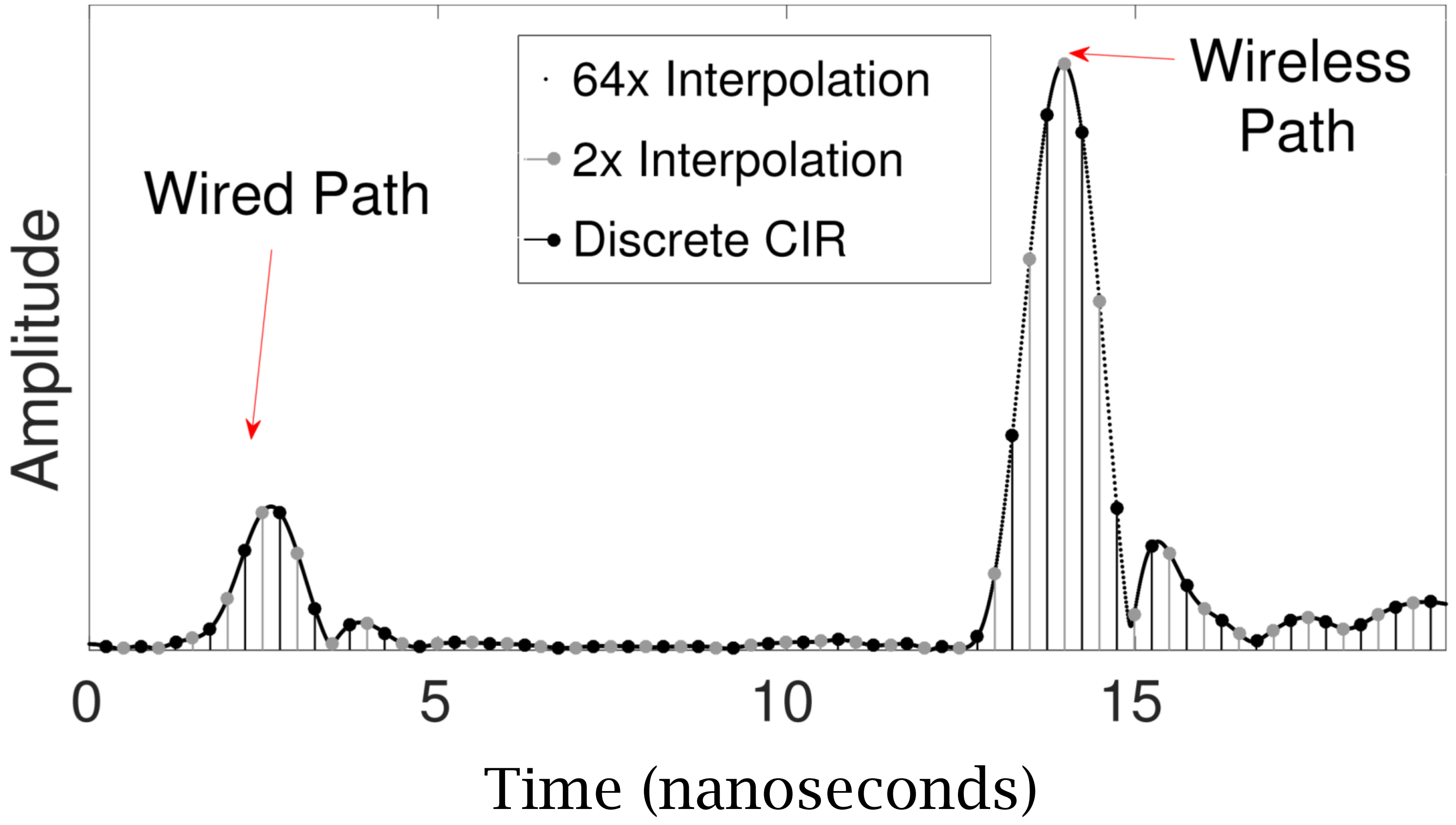


dhekne2@Illinois.edu

End of Presentation

Backup Slides

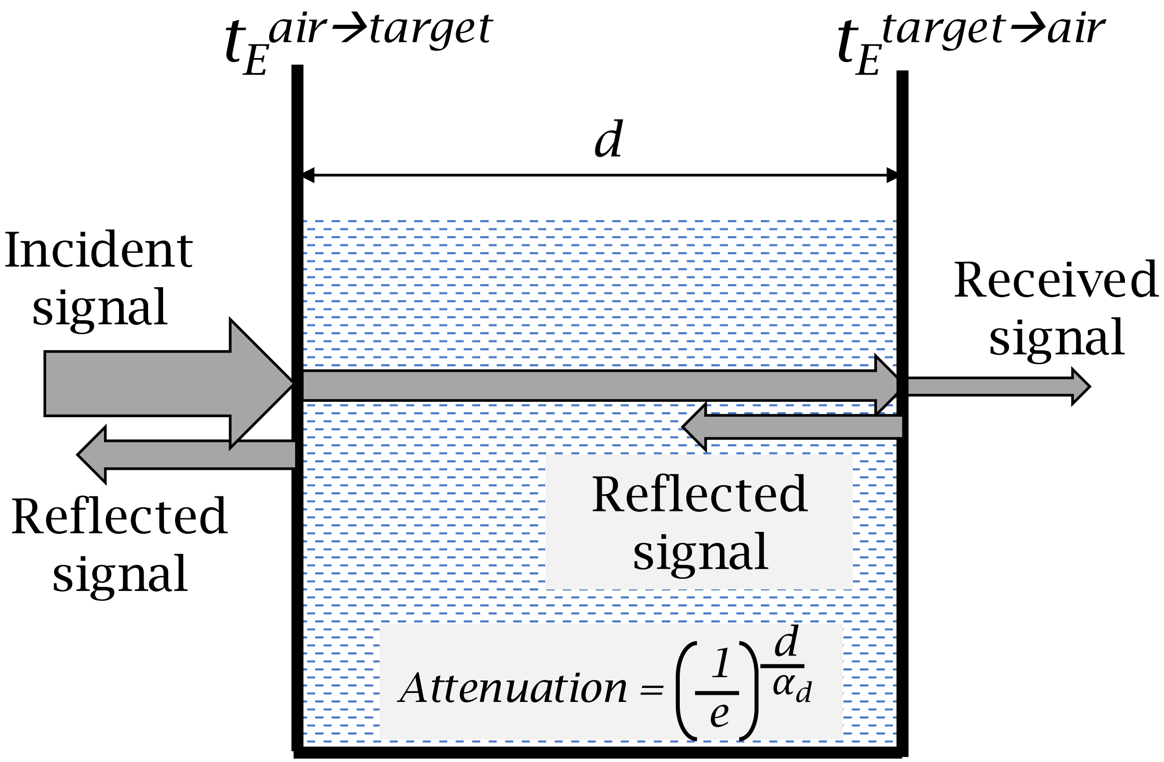
Discrete CIR to interpolated



Impedance Mismatch in Liquids

$$t_E = \frac{2Z_2}{Z_2 + Z_1}$$

Type equation here.



Container Compensation

- Empty container's complex permittivity is also obtained with the same technique
- Our container was made of acrylic with permittivity of about 3.45+0*j*

$$\frac{RSSI_{liq}}{RSSI_{air}} = t_E^{air \rightarrow c} . t_E^{c \rightarrow liq} . t_E^{liq \rightarrow c} . t_E^{c \rightarrow air} . \left(\frac{1}{e}\right)^{\frac{L_{liq}}{\alpha_d}}$$

Diffraction Problems

- Diffraction can cause signals to go around an obstacle

- Diffracted signals may arrive before the refracted signal!
- This corrupts the time of flight estimate
- We deal with diffraction by using a large container – more than 4 wavelengths on either side

Extreme Conductivity

- Extremely conductive liquids, such as 1 molar saline solution, will not allow RF signals to penetrate
- LiquID will fail to estimate the permittivity of such liquids
- However, it can definitely indicate that the liquid is extremely conductive.

Tagscan

- Only differentiates between liquid with a certain phase relationship with each other.
- Lacks any notion of actual delay or time of flight

- Works only with liquids with similar refractive index to each other.

Tagscan (cont…)

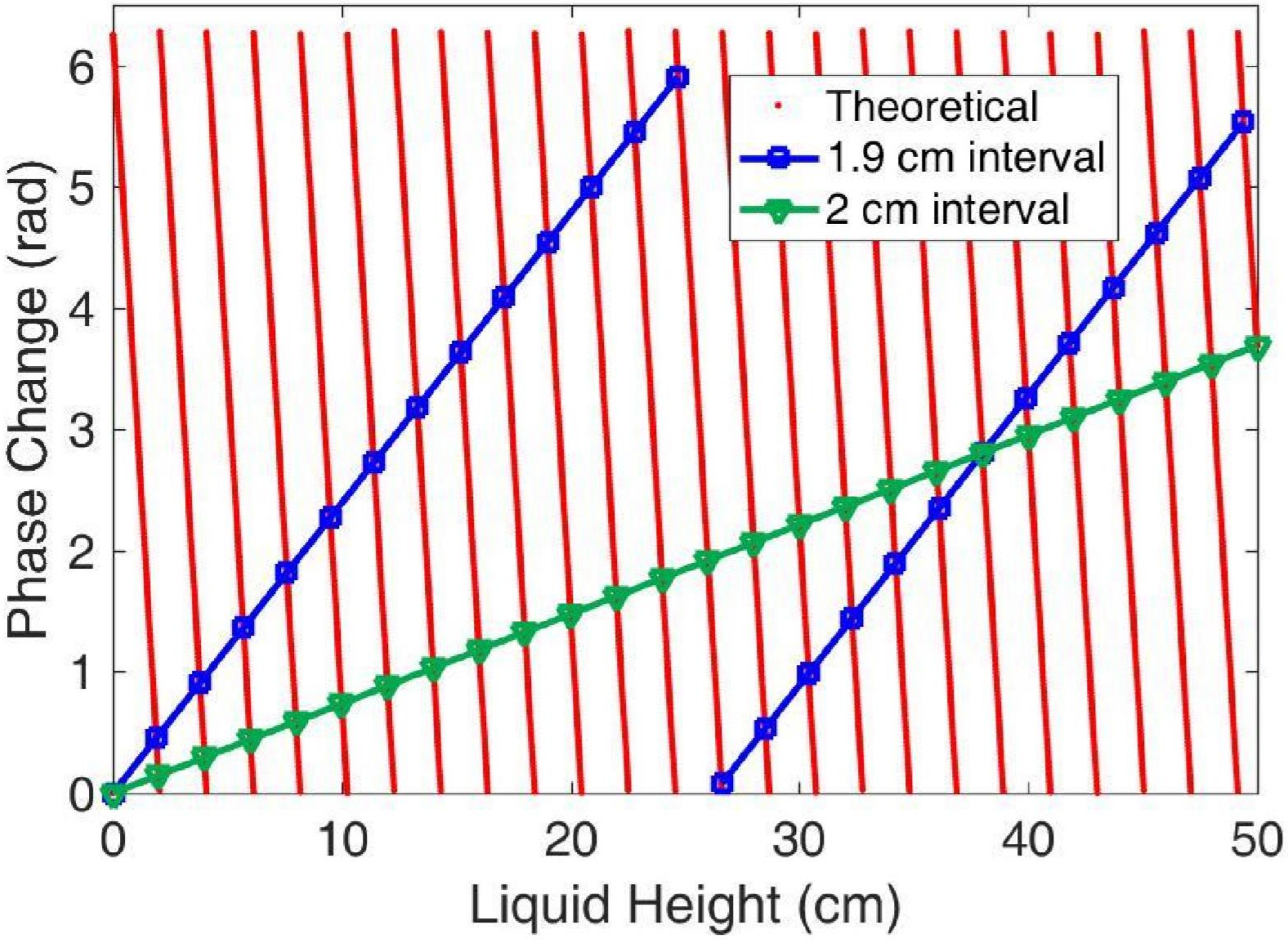


Fig. Different slopes with different intervals.

Permittivity from RI and AF

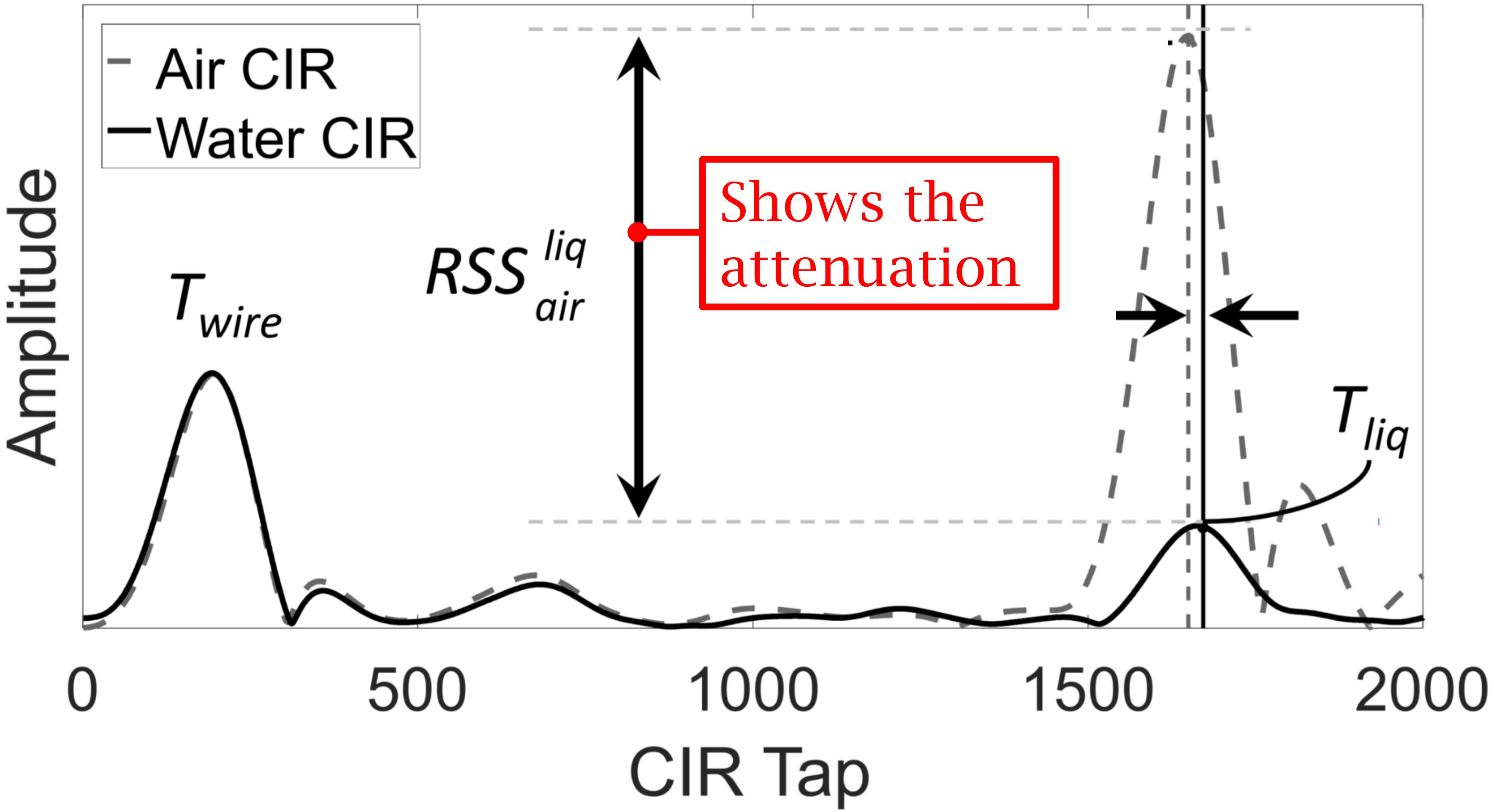
$$Refractive\ Index = \sqrt{\frac{1}{2}\epsilon' \left\{ \sqrt{1 + \left(\frac{\epsilon''}{\epsilon'}\right)^2} + 1 \right\}}$$

$$Attenuation\ Factor = \frac{\lambda_0}{2\pi} \sqrt{\frac{2}{\epsilon' \left(\sqrt{1 + \left(\frac{\epsilon''}{\epsilon'}\right)^2} - 1 \right)}}$$

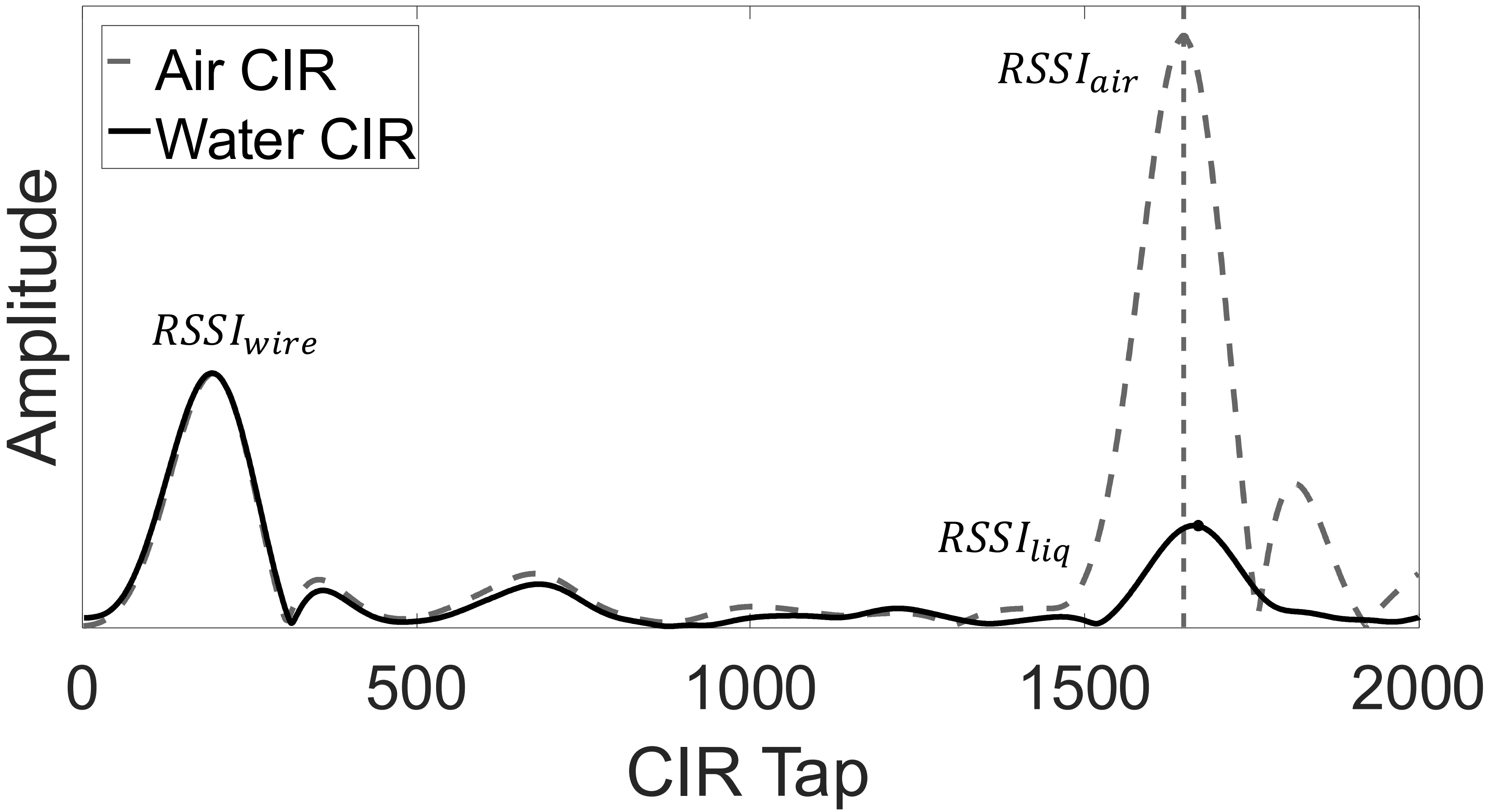
Solve for ϵ' and ϵ''

End of backup slides

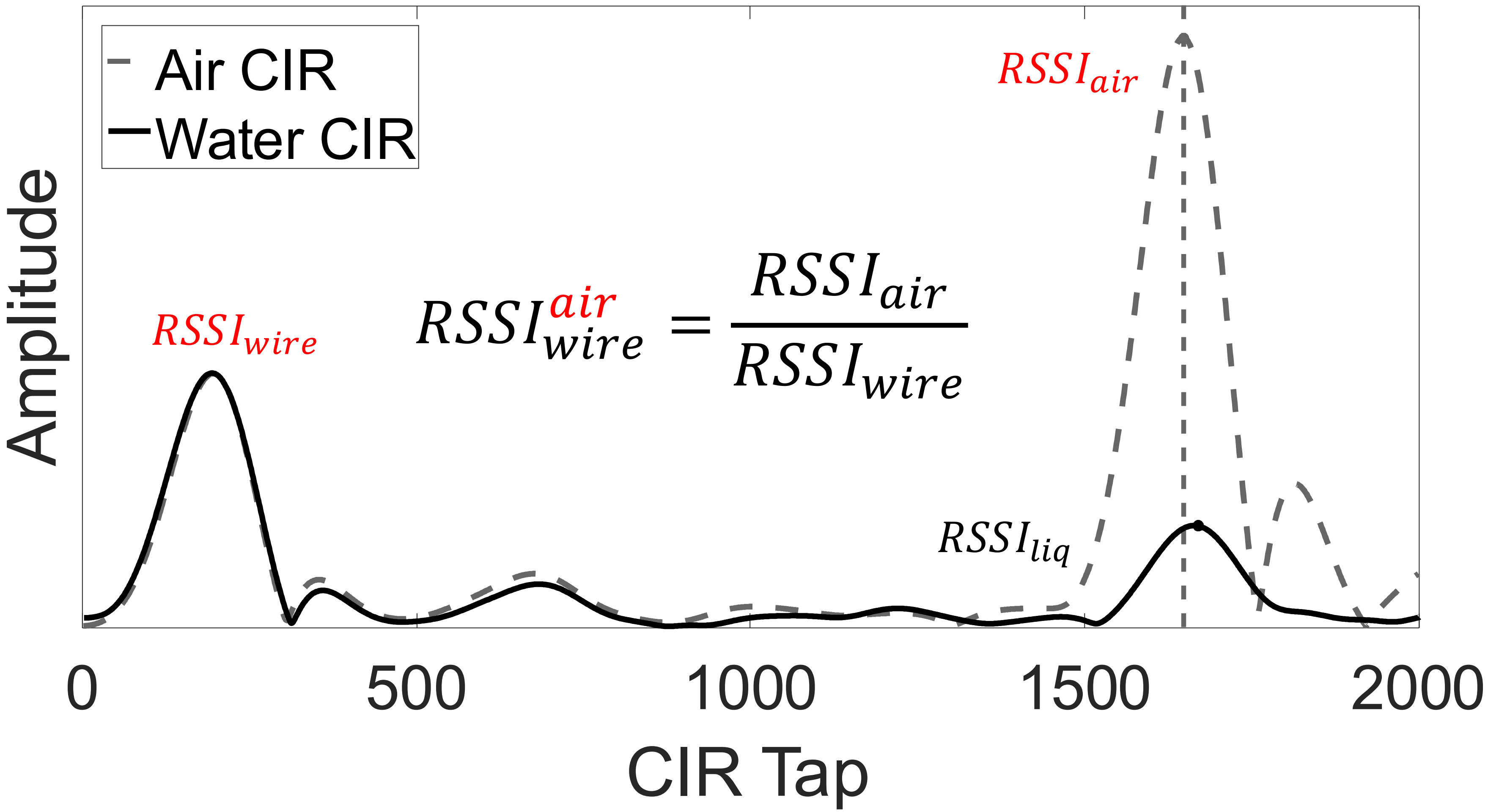
Estimating Attenuation



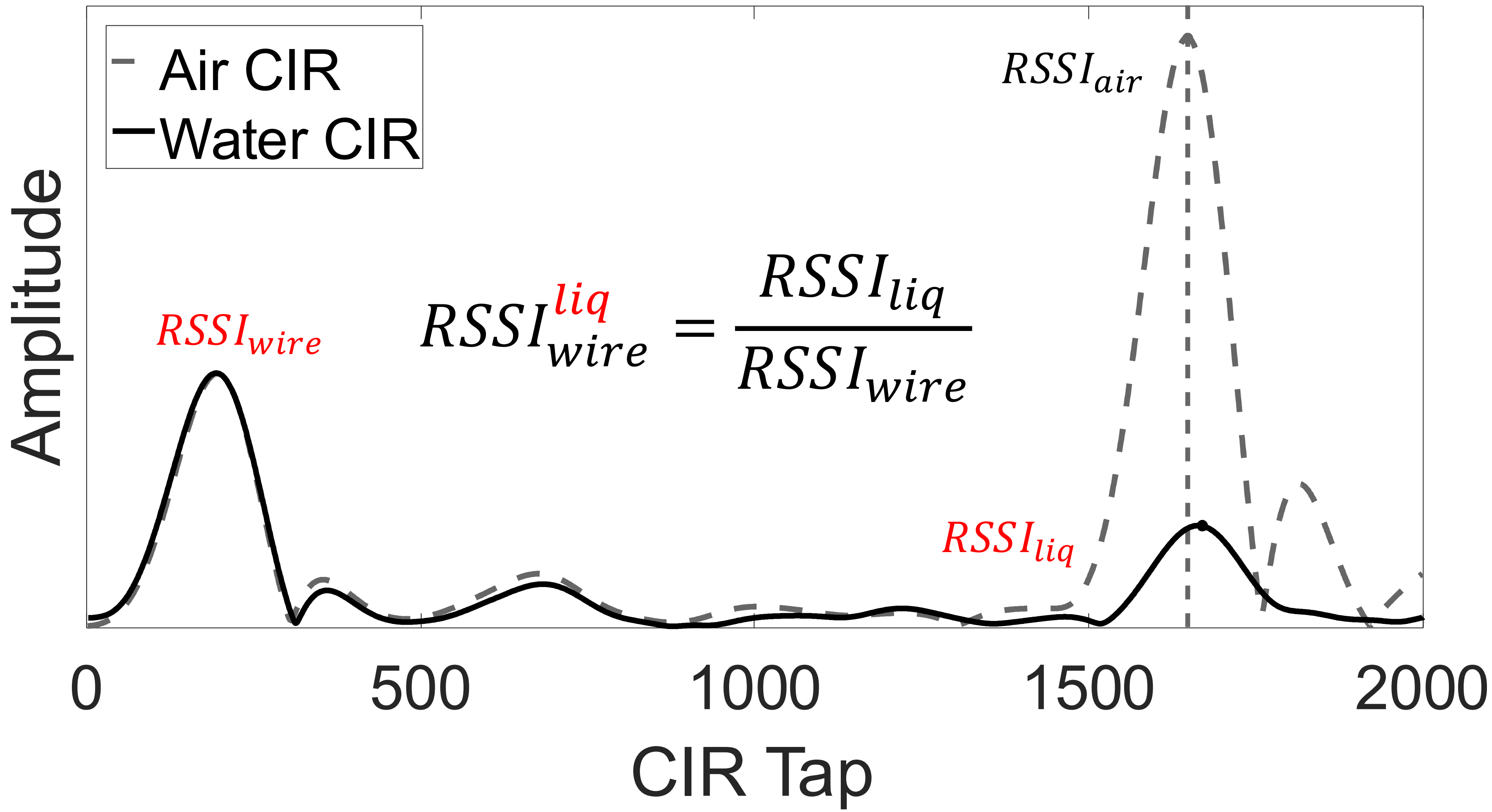
Estimating Attenuation



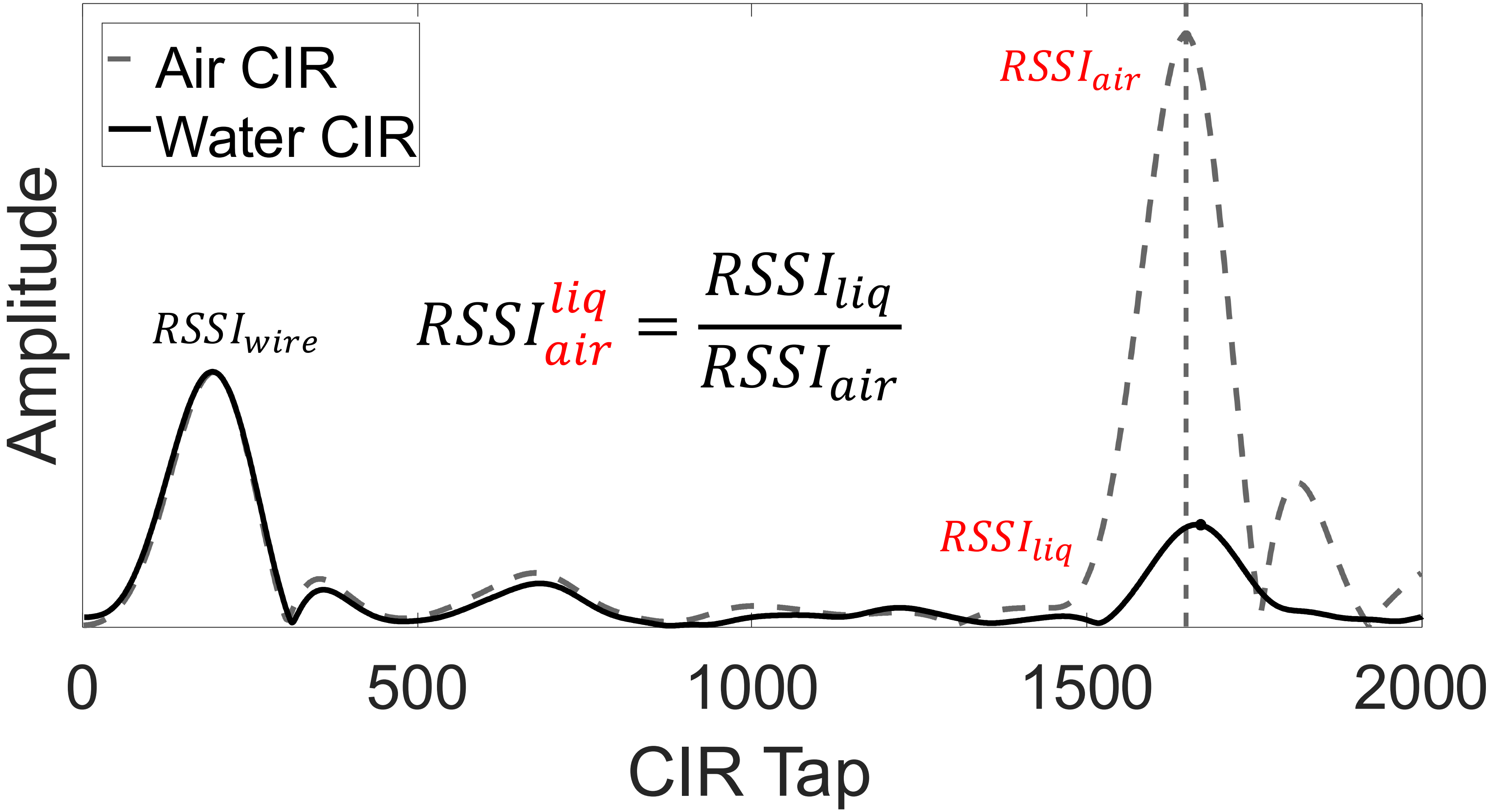
Double Differencing – RSSI



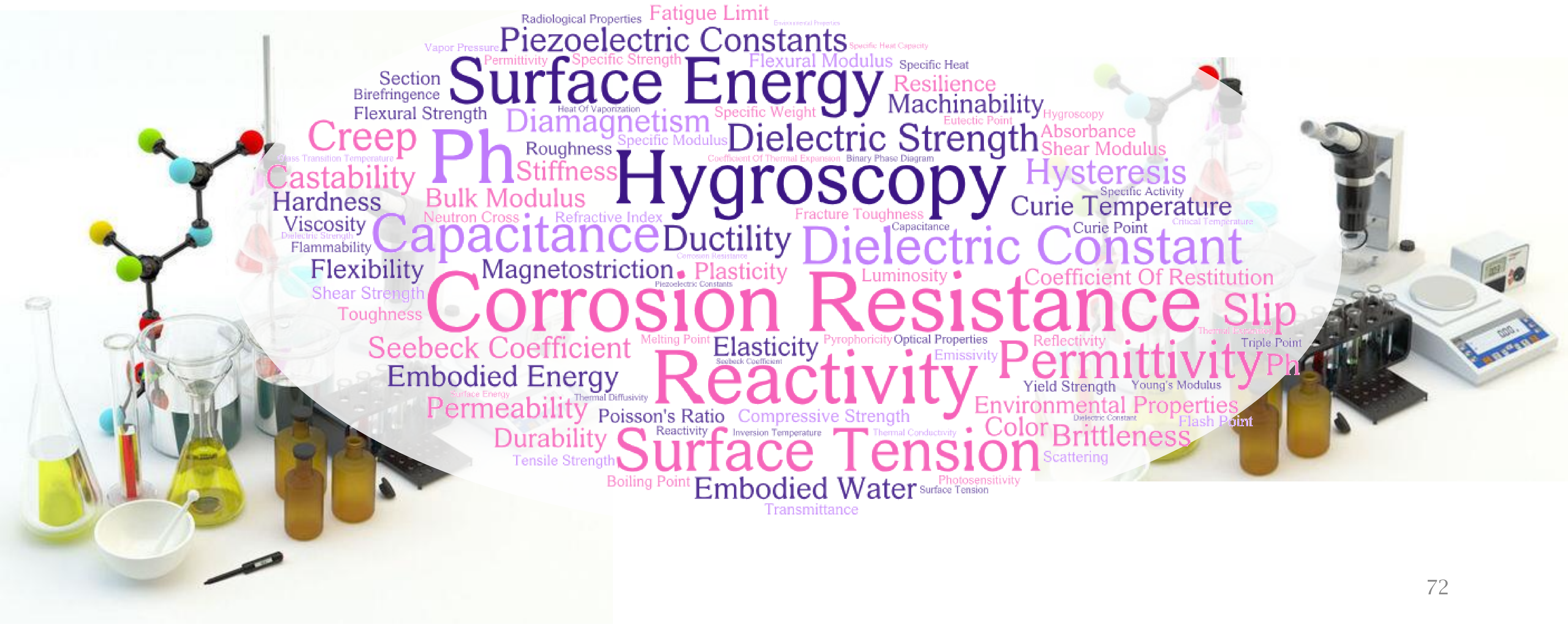
Estimating Attenuation



Estimating Attenuation



Existing Solutions – [Deprecated]



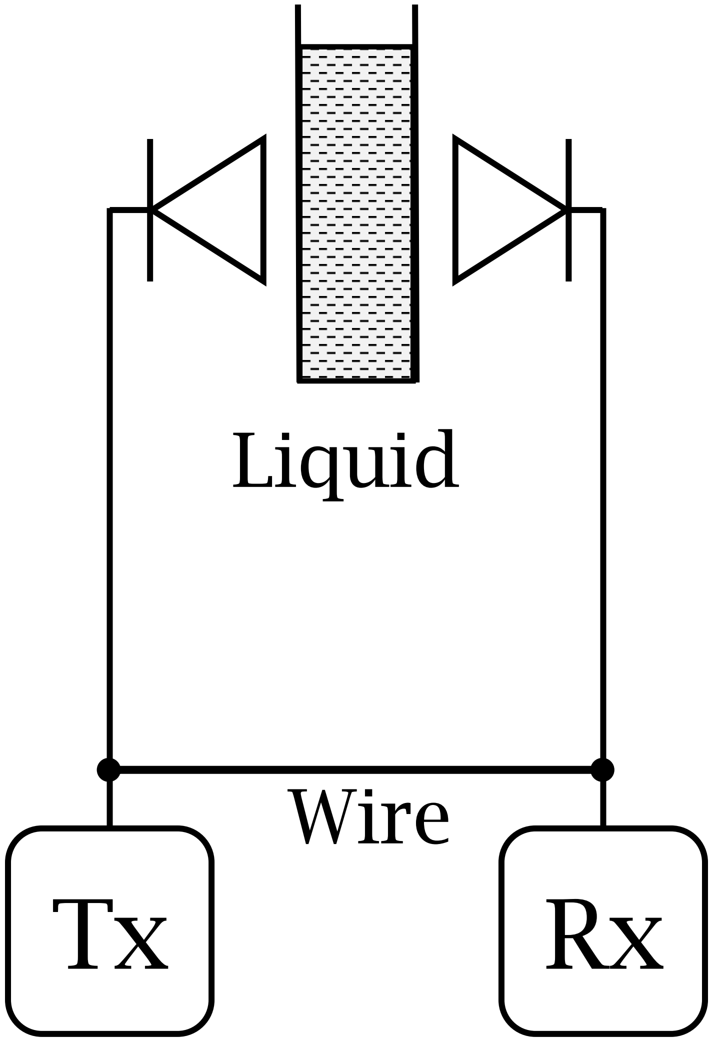
State-of-the-Art is Insufficient

- Ultra-wideband radios use 1GHz bandwidth
- High sampling rate allows tens of centimeters of precision

- Great for localization, yet insufficient for LiquID

Introducing a Wired Path

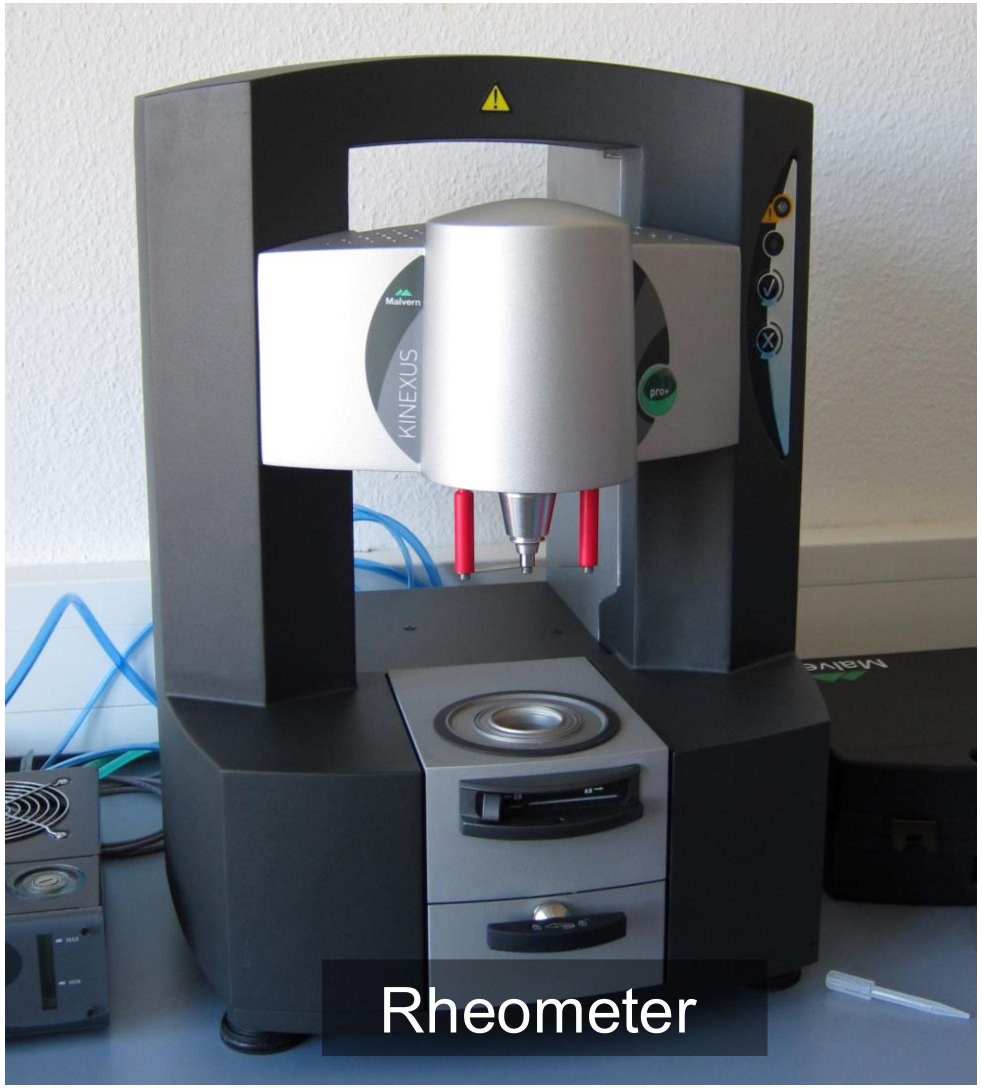
- Create a reference path
- Allows phase based ToF measurements
- Allows received signal strength comparisons



Existing Solutions

- Light based techniques fail for opaque materials

- Labs typically perform destructive analysis



Food Quality Assurance

Refractive Indices at 4GHz

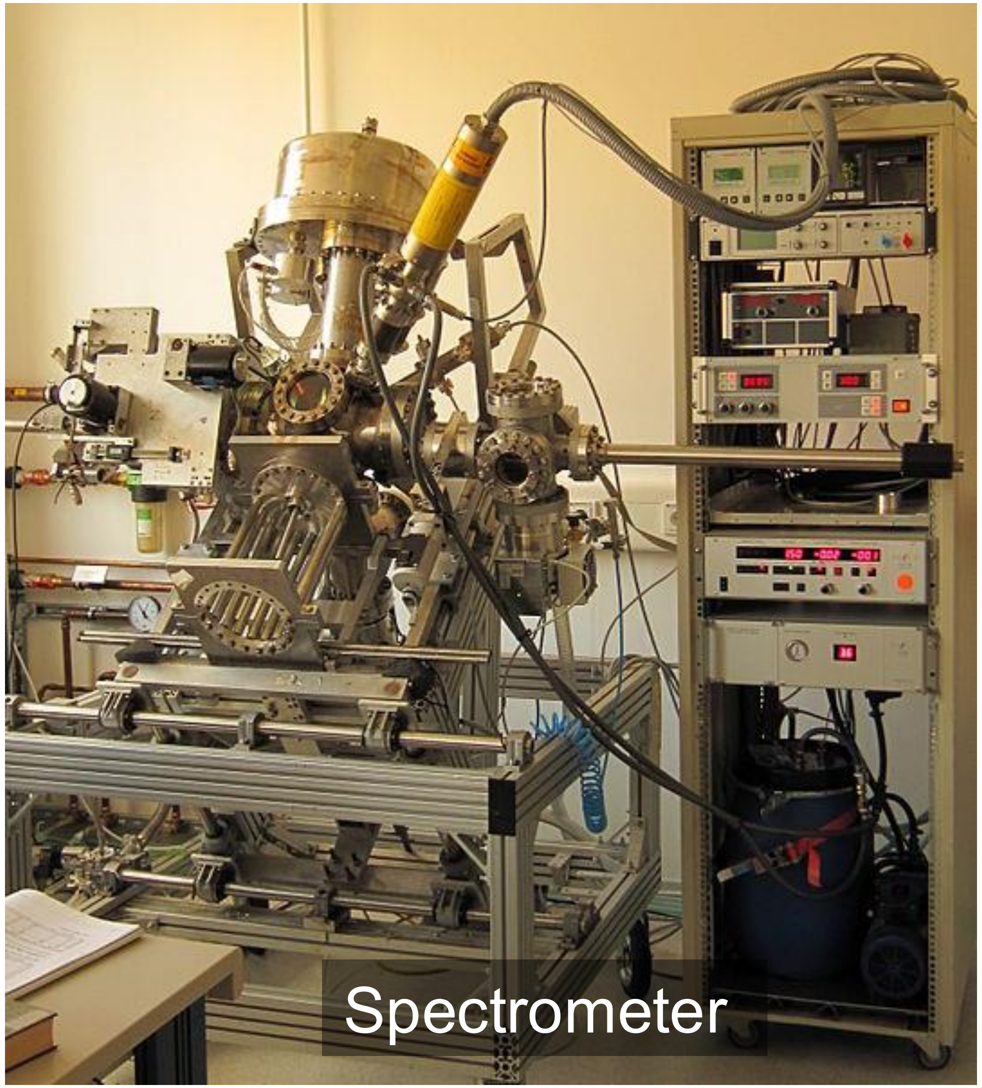
Existing Solutions

- Light based techniques fail for opaque materials

Refractometer

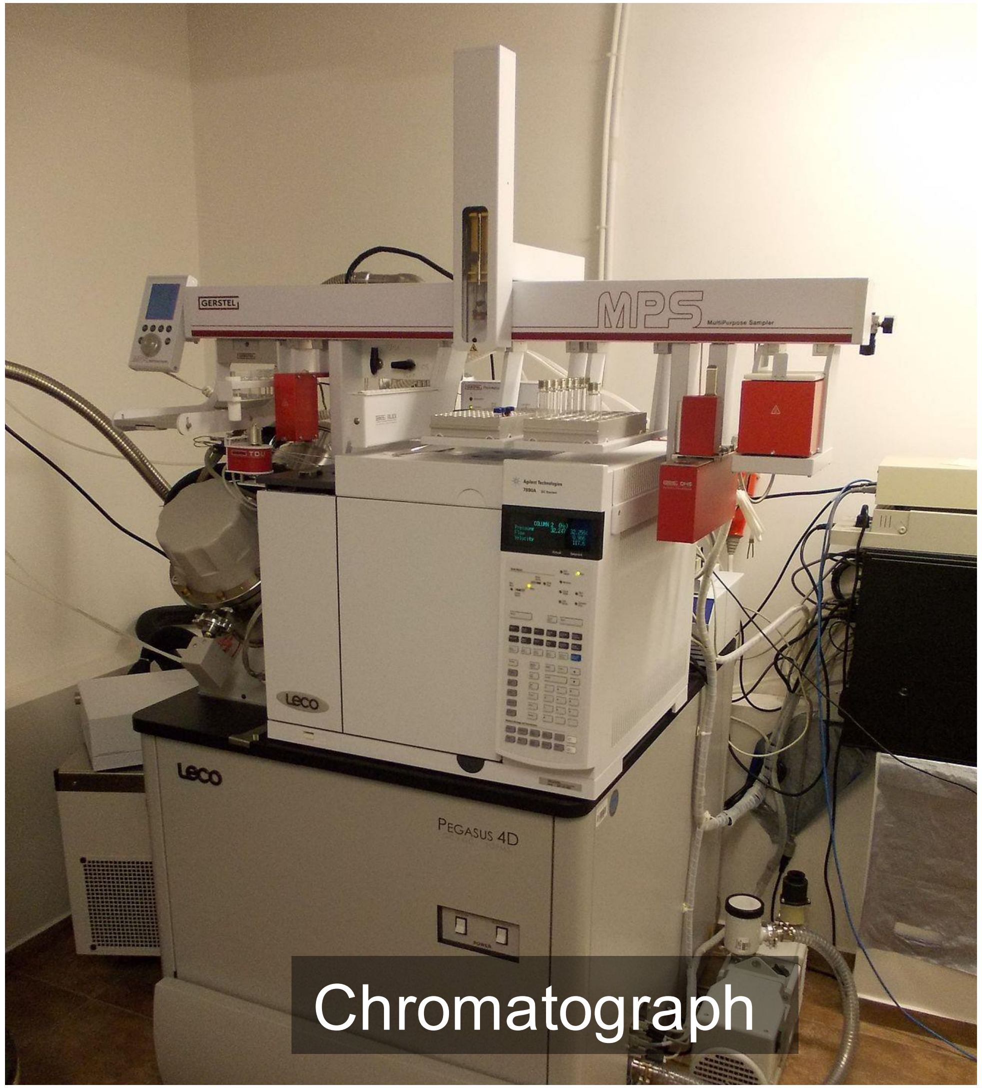
Existing Solutions

- Light based techniques fail for opaque materials
- Spectrometers and chromatographers are invasive and destructive



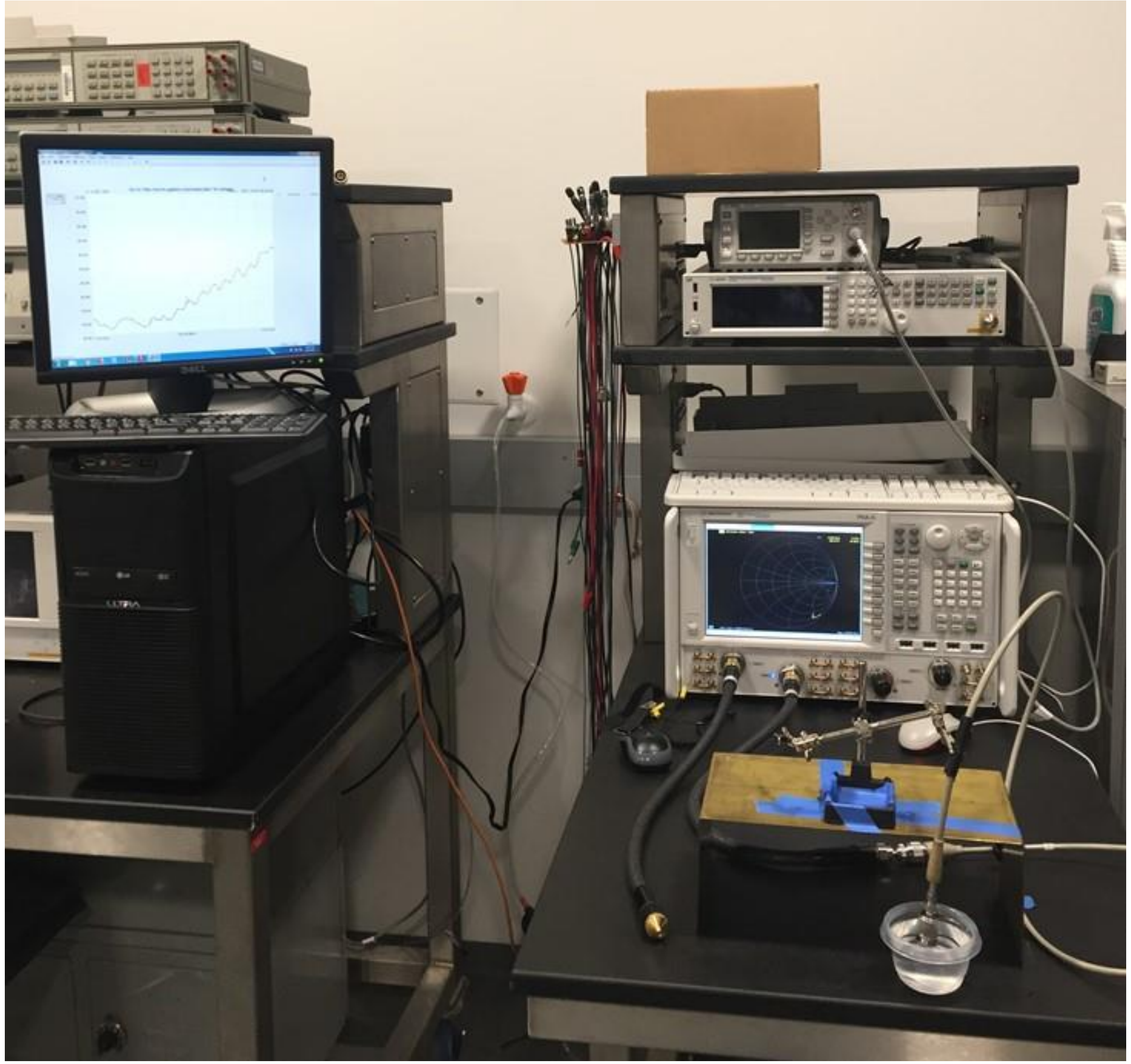
Existing Solutions

- Light based techniques fail for opaque materials
- Spectrometers and chromatographers are invasive and destructive
- They use heat, and chemical analysis



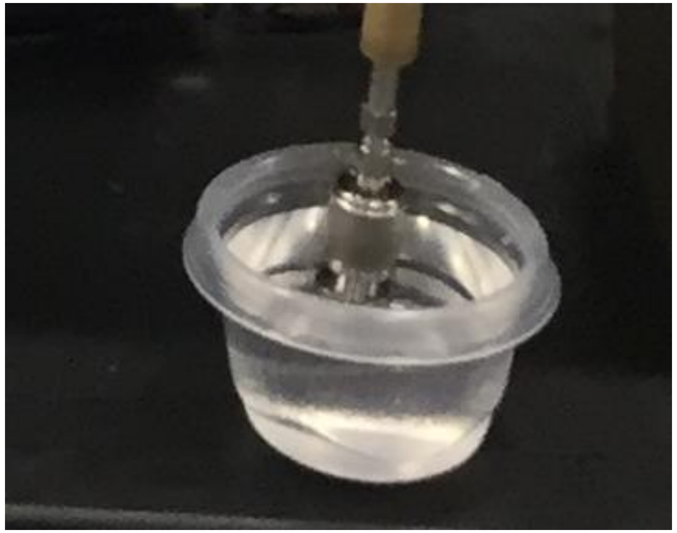
Chromatograph

Existing Solutions



- VNA + Dielectric Probe

- Expensive >$100,000
- Invasive – needs dipping a probe in the liquid



A function of Permittivity

Refractive index = f_1 (Permittivity)

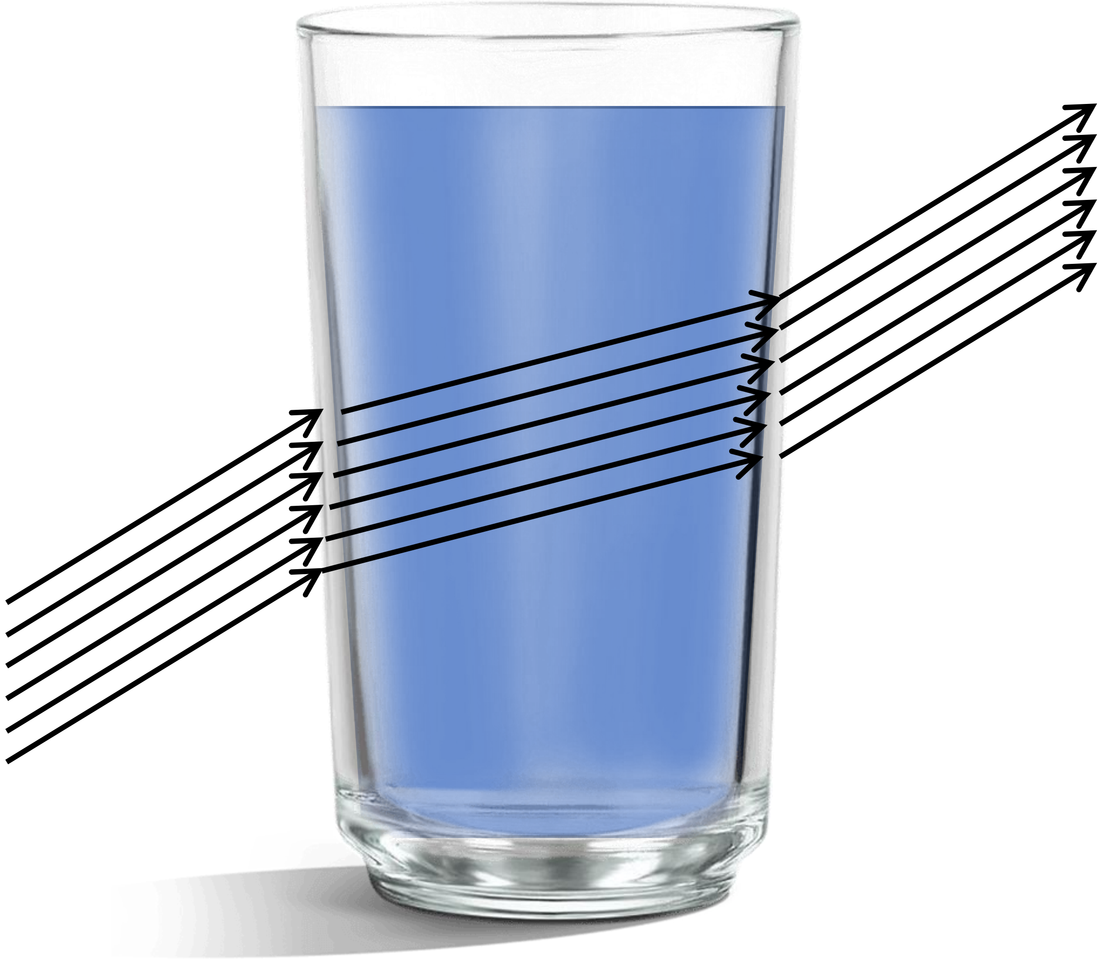
Attenuation Factor = f_2 (Permittivity)

Airport Security

LiquID

Refractive Index – Snell's Law?

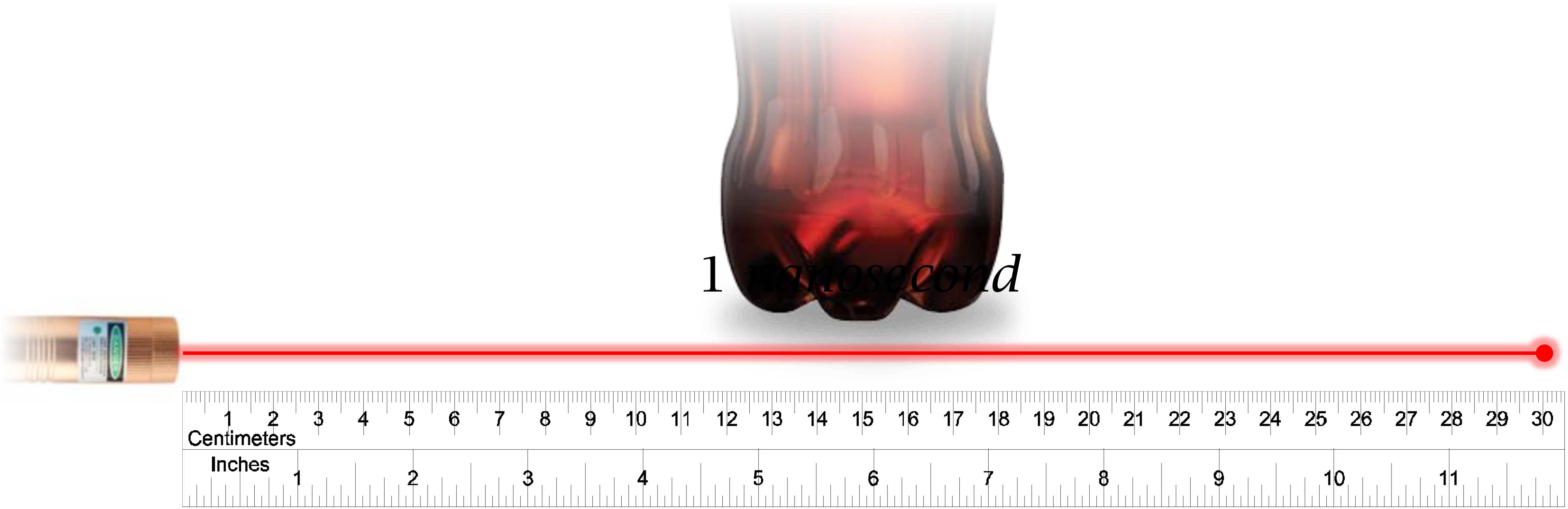
- Measured using light beams and Snell's law
- A similar approach with wireless would require impractical pencil beams



So near, yet so far!

~10 *picoseconds*

1 *nanosecond*

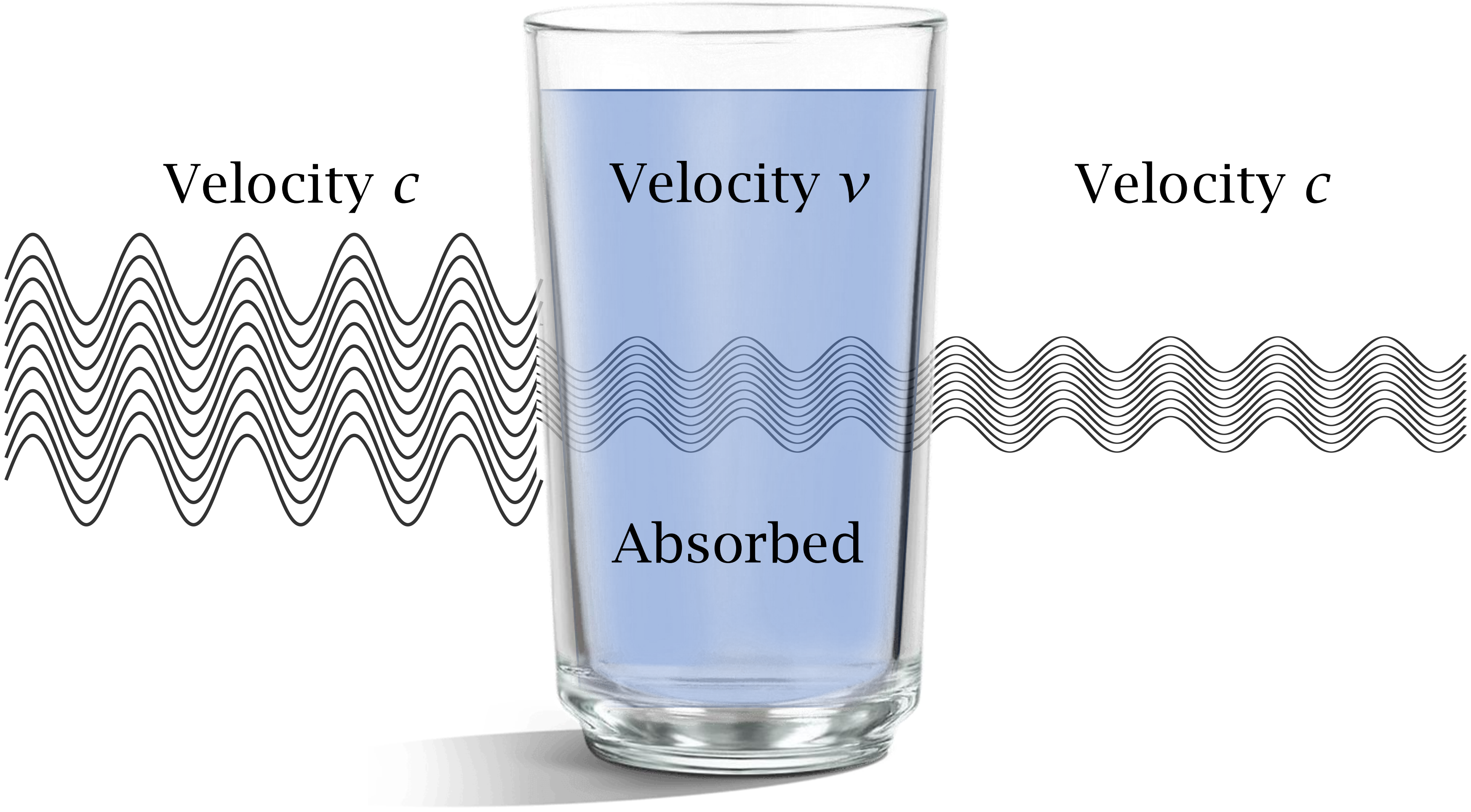


Opportunity

- Ultra-wideband radios give ToF in nanoseconds
  - Can we do better?
  - Understanding the internals of UWB may hold the answer

- Use the phase of the receive signal
  - Phase change is a function of the slowdown
  - However, phase wraps

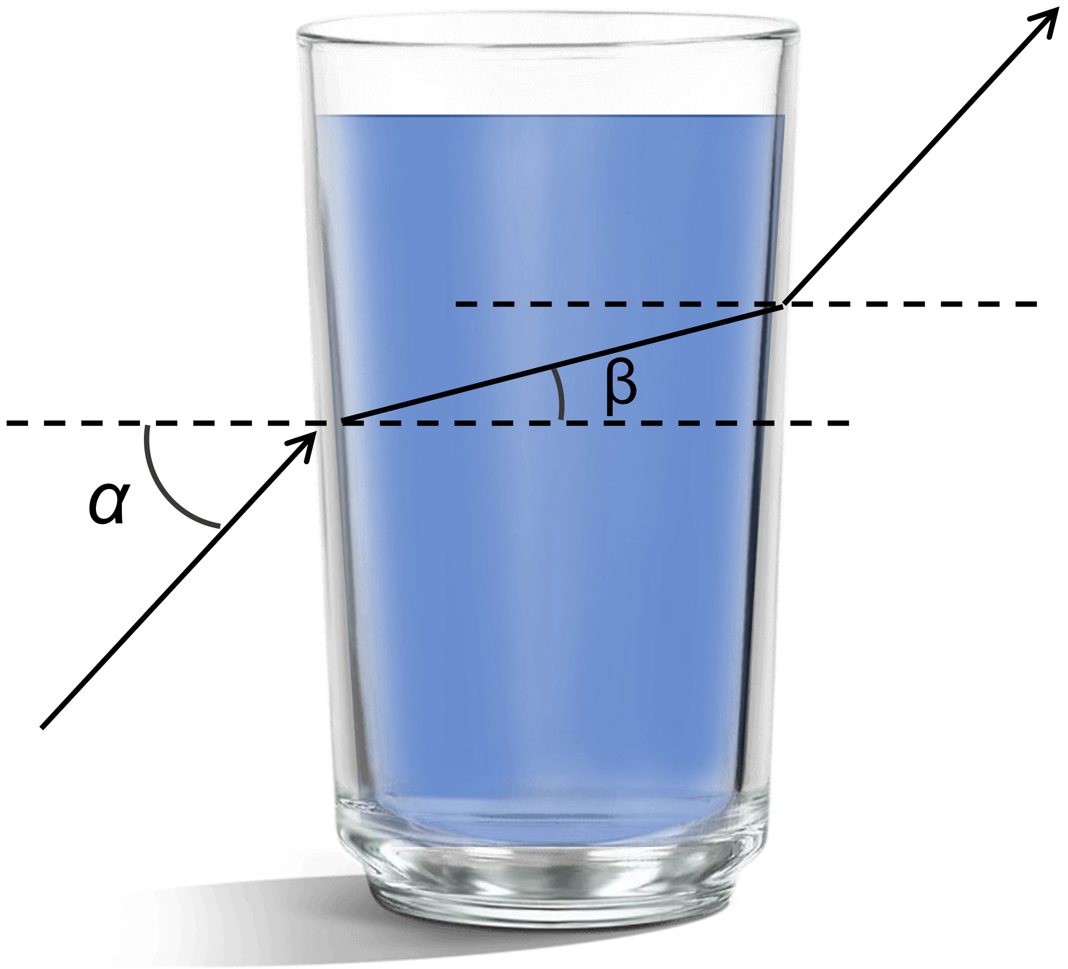
Key Properties of Liquid



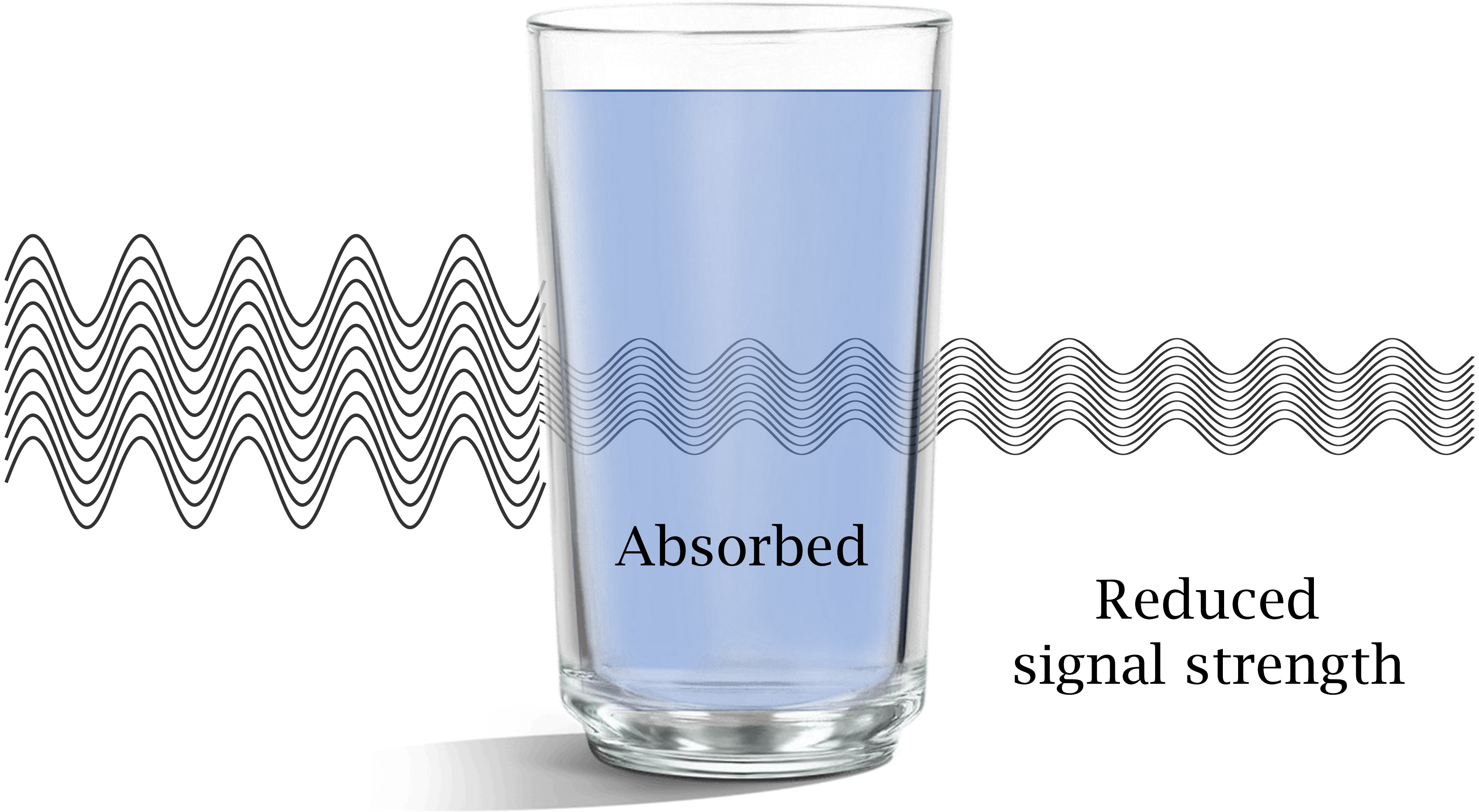
Refractive Index – Snell's Law?

- Measured using bending light beams and Snell's law

"the general case of arbitrary dielectrics and oblique incidence is of great complexity" –Von Hippel



Attenuation Factor



ToF gives Refractive Index

$$ToF_{liq} - ToF_{air} = \frac{\boldsymbol{d}}{\boldsymbol{v}} - \frac{\boldsymbol{d}}{\boldsymbol{c}}$$

Only Unknown

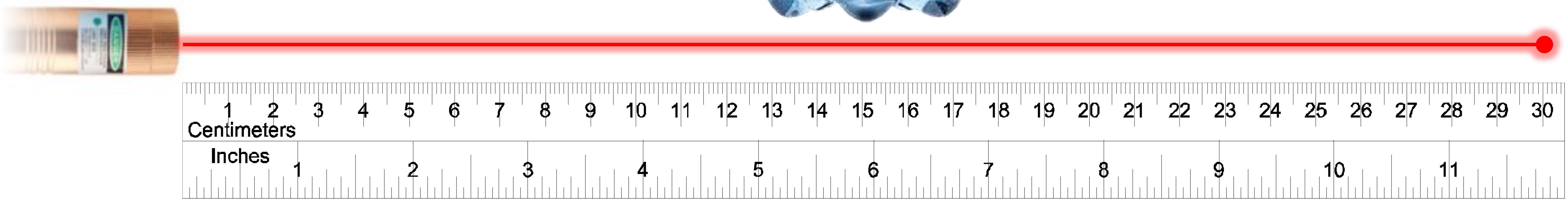
$$Refractive\ Index = \frac{c}{v}$$

So near, yet so far!

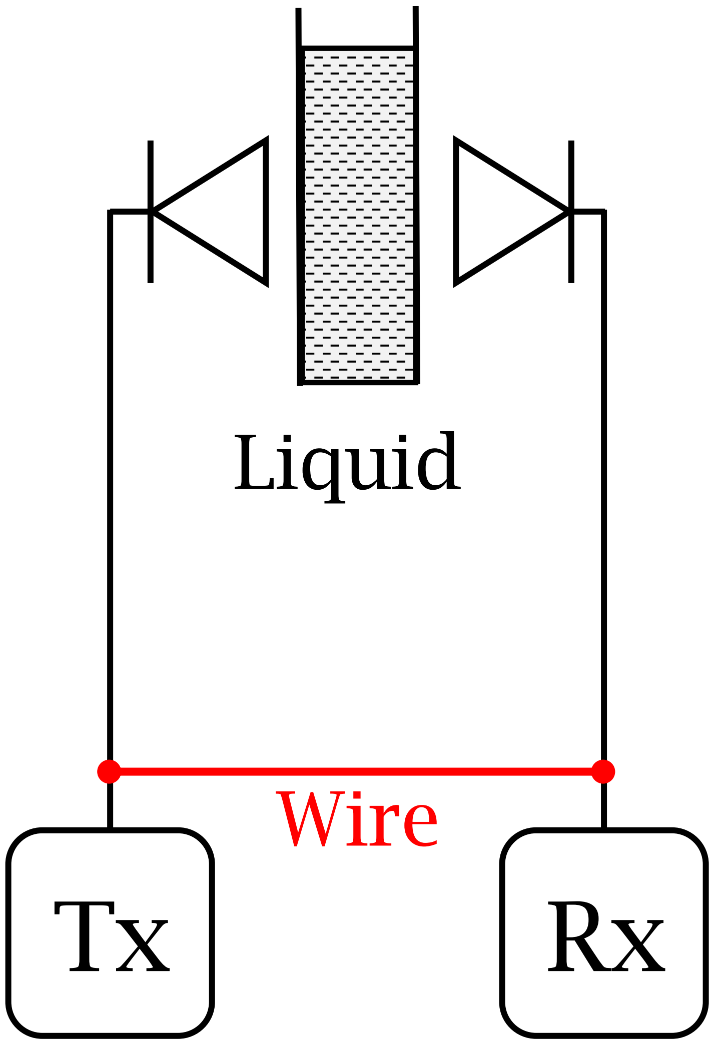
~10 *picoseconds*

Soybean Oil?

1 *nanosecond*



Our Contributions



Limitations and Future Work

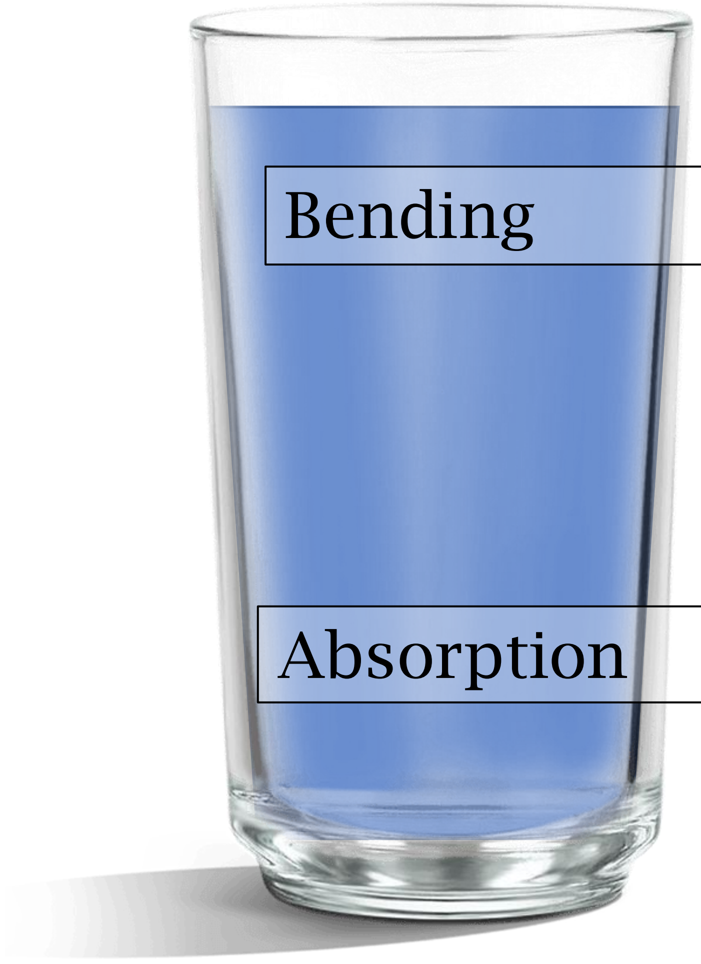
- Identification of trace adulteration is a challenge
- Circular and any-shaped container compensation

- Extend to solids – detect various layers
- Extend to many frequencies – provide better identification
- Realize the applications – simplify airport security

Conclusion

- Determining permittivity enables liquid identification
- LiquID performs precise time of flight measurements using UWB radios
- LiquID achieves the required precision for measuring two basic physical properties of liquids leading to identification

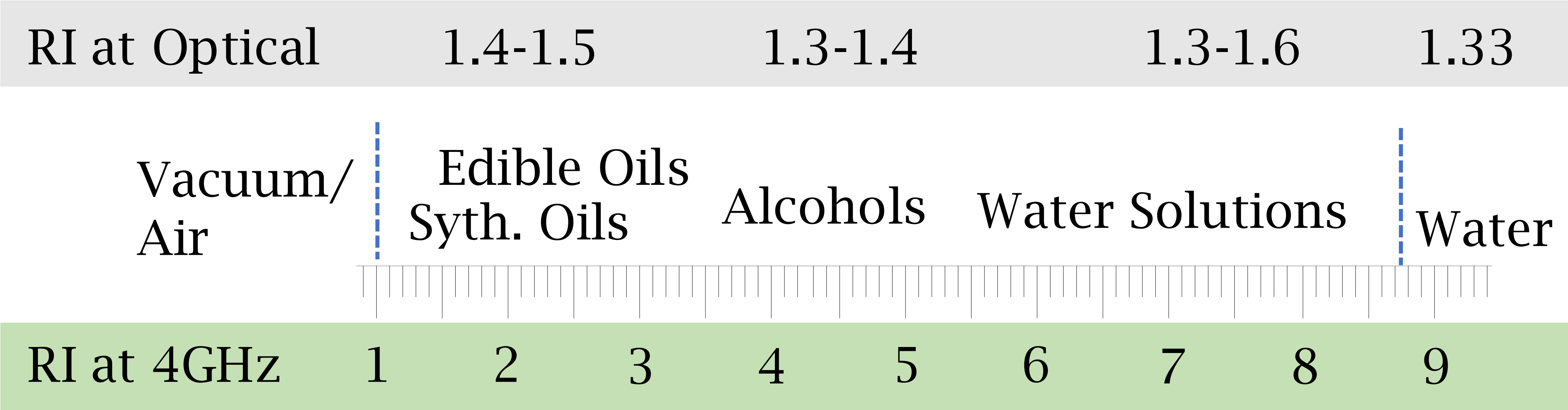
Key Properties of Liquid



Bending → Refractive Index

Absorption → Attenuation Factor

Refractive Indices at 4GHz



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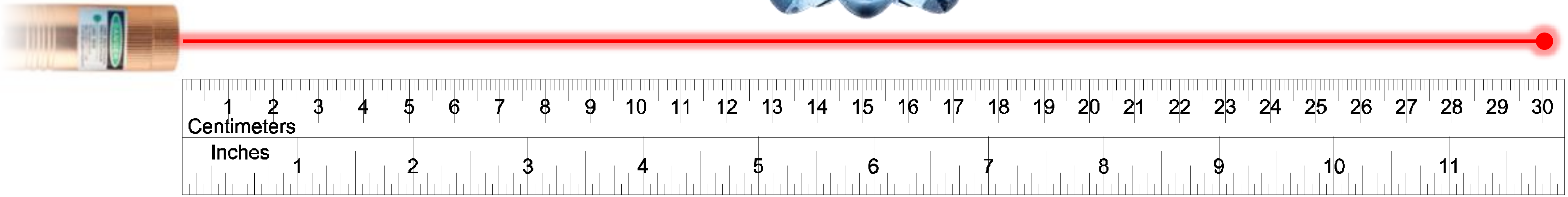
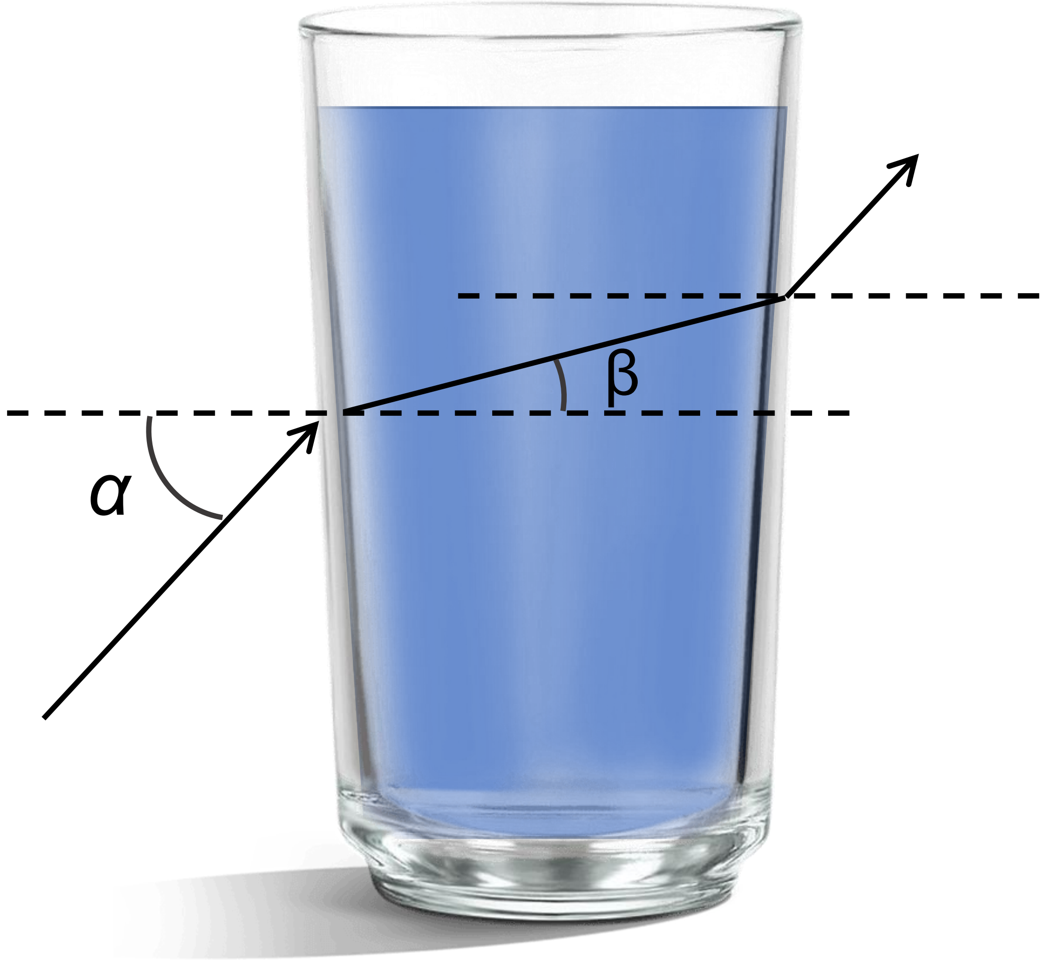


Refractive Index

$$R.I. = \frac{sin\alpha}{sin\beta}$$



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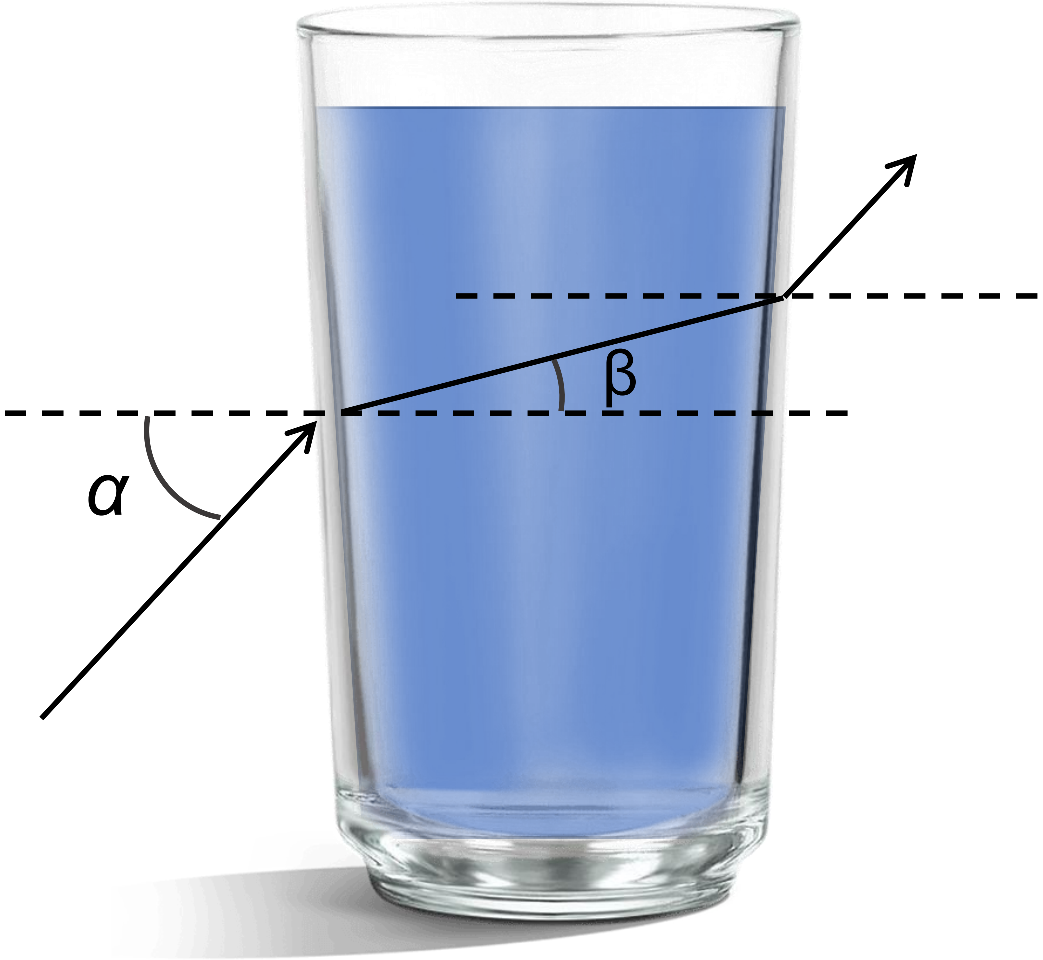
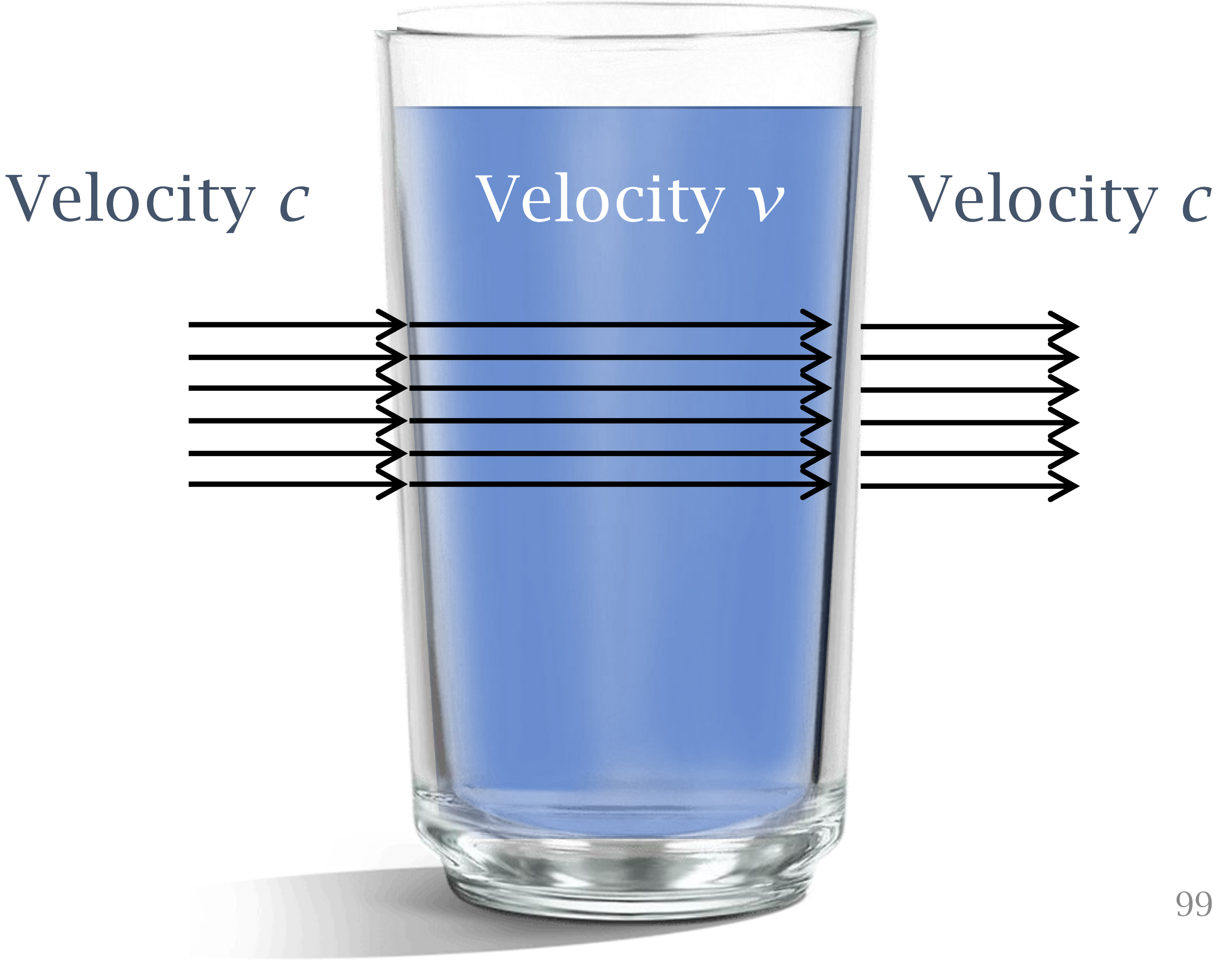
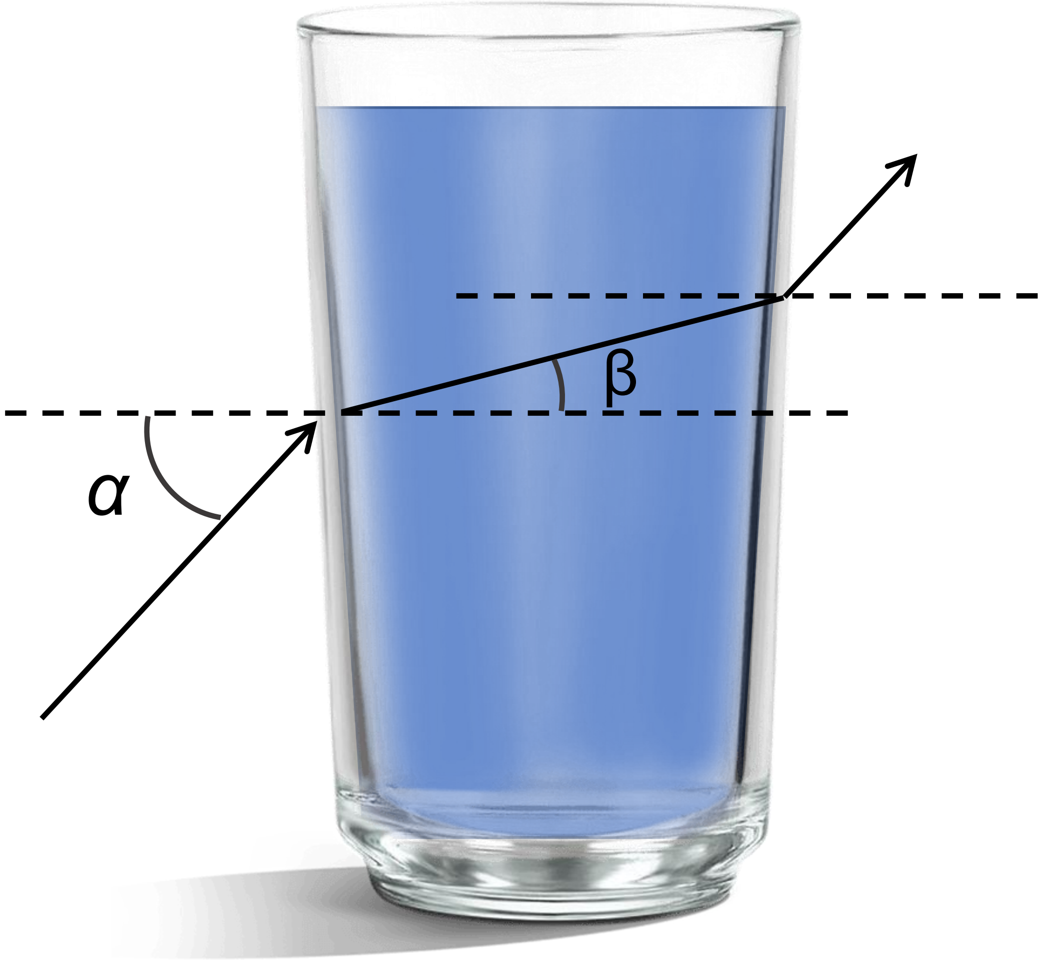
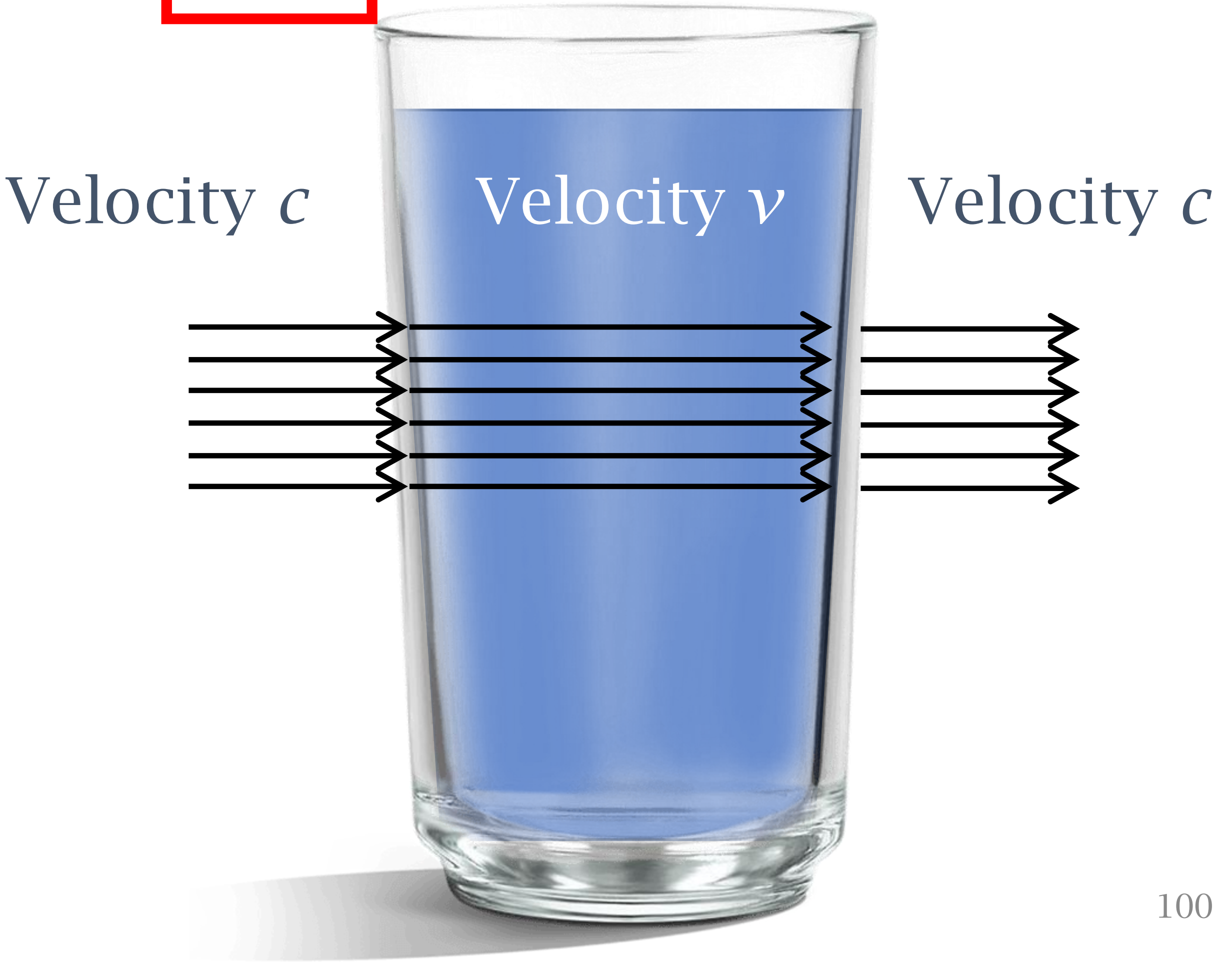




Refractive Index

$$R.I. = \frac{\sin\alpha}{\sin\beta} = \boxed{\frac{c}{v}}$$





Results – Identification