RF Power Transmission and Antenna Design

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Nathan Song
Nikhil Maserang

Abstract

We aimed to explore facets of center-fed dipole antennas, such as:

A. The relationship between antenna length, induced voltage, and received power.
B. The relationship between distance and received power.

We then attempted to confirm our results by predicting the turn-on voltage of an unknown LED.

Through these experiments we confirmed basic properties of half-wavelength dipole antennas.

Motivation

- Antennas are awesome!
- Basically magic, but in real life.
- Saw a cool demo of wireless lighting an LED.

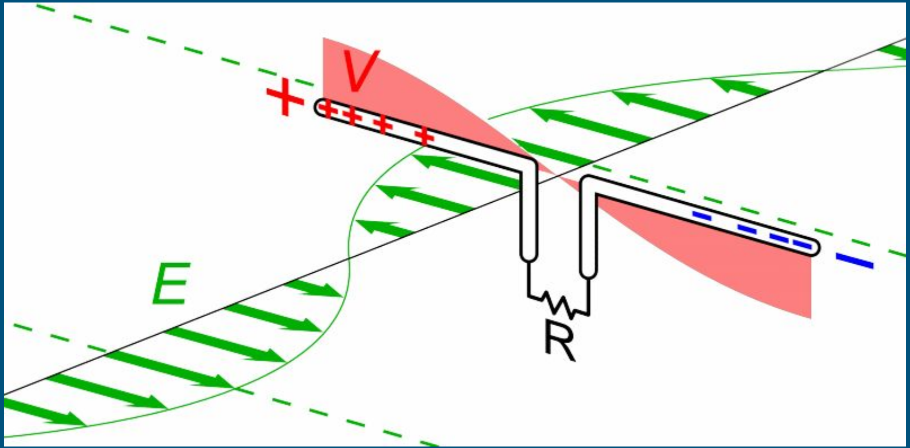
We wanted to show that a half-wavelength dipole was the best at capturing power, and that the power dropped off with the inverse square of the distance.

We also wanted to learn how to use new tools, such as the soldering iron, and learn more about antenna physics in general.

You're a wizard, Harry!!

Basic Theory

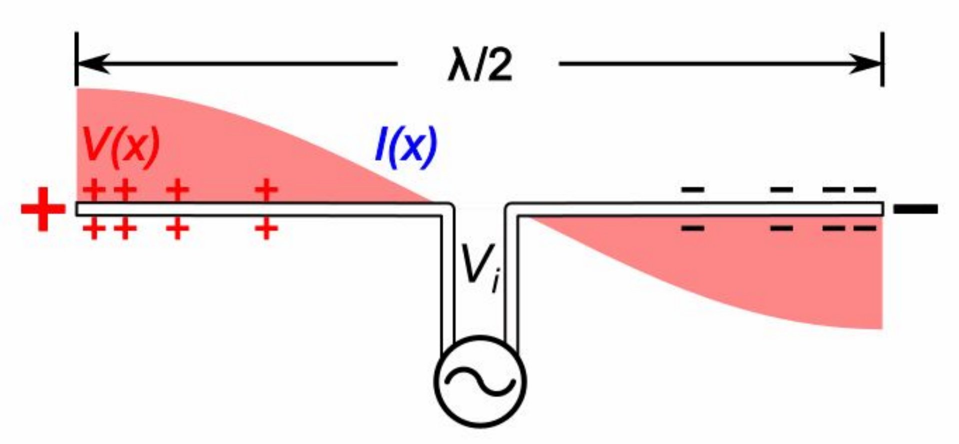
Radios emit electromagnetic waves at radio frequencies (RF). The electric field component of this wave can, if oriented properly, interact with the wire, inducing a current in it (and an emf across it).



https://commons.wikimedia.org/wiki/File:Dipole_receiving_antenna_animation_6_800x394x150ms.gif

Basic Theory

The current and voltage act like standing waves in the antenna. Current at the ends must be zero, while the voltage must be maximum, so the ends act like nodes and antinodes for current and voltage respectively.



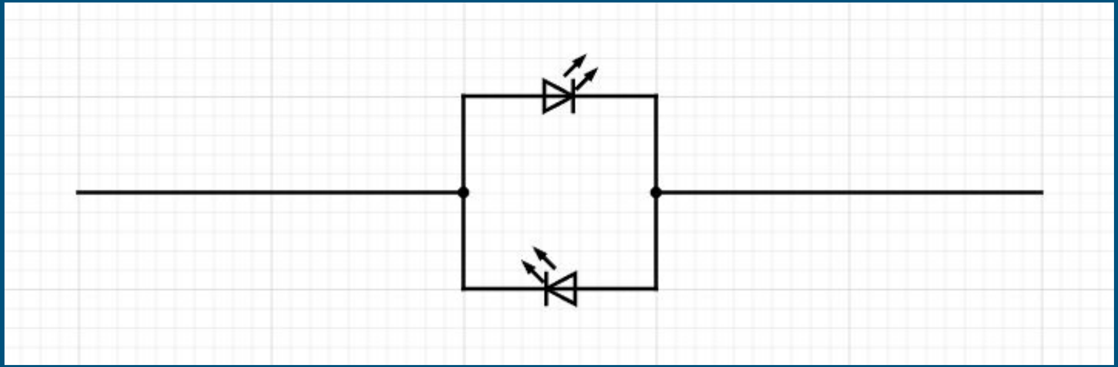
https://commons.wikimedia.org/wiki/File:Dipole_antenna_standing_waves_animation_6_-_5fps.gif

Basic Theory

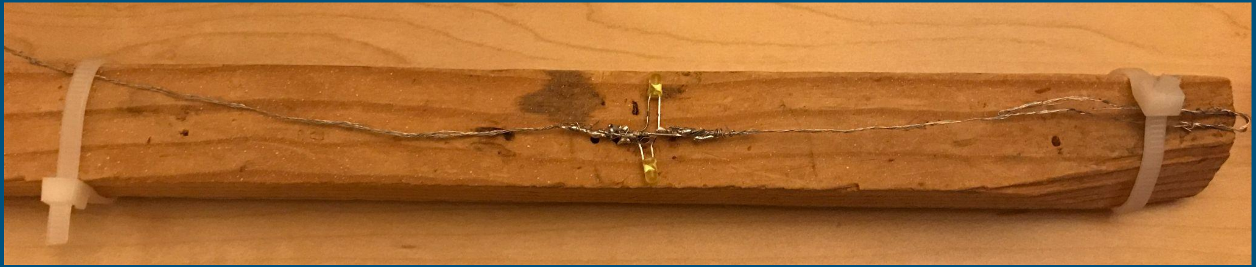
LEDs are polar electrical components that have a specific “turn on voltage”.

This is the voltage that needs to be placed across the leads for a current to flow.

We constructed an antenna circuit with two oppositely polarized LEDs in parallel; this allows the AC current induced by the RF signal to flow in both directions:

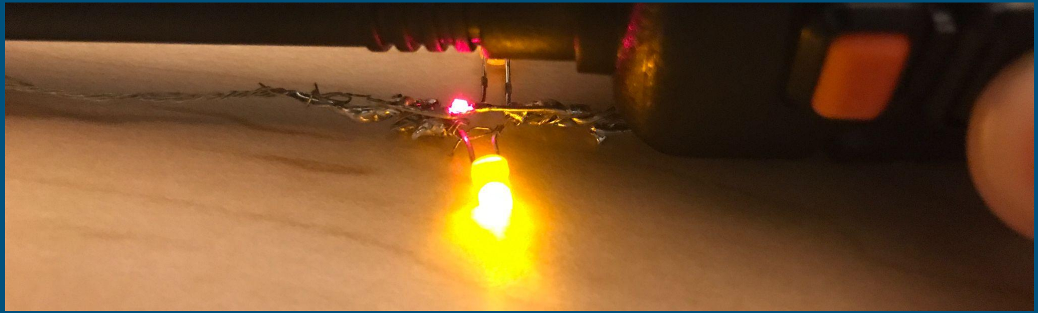


Antenna: Prototype 1

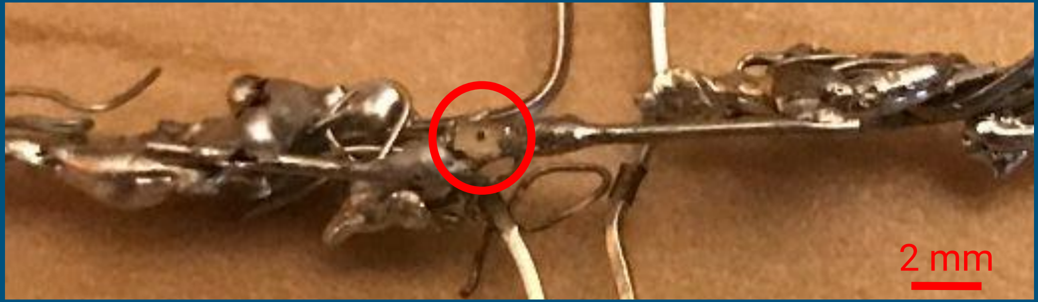


High quality soldering job…

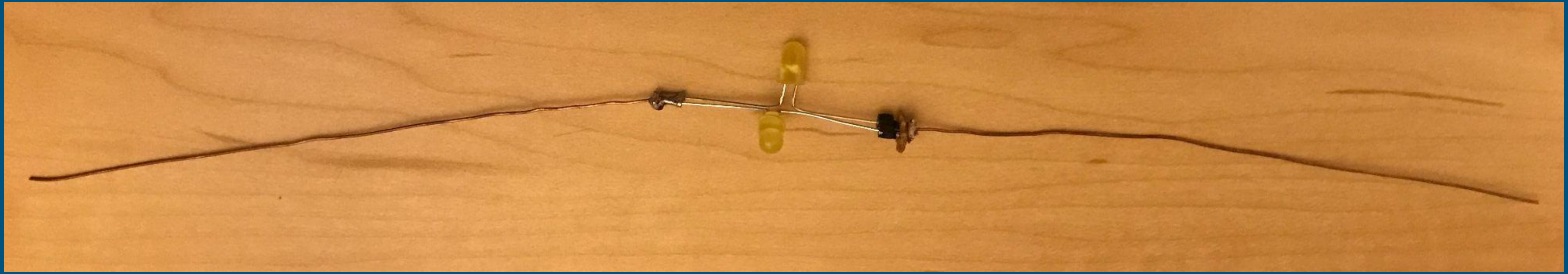
Antenna: Prototype 1



High quality soldering job…

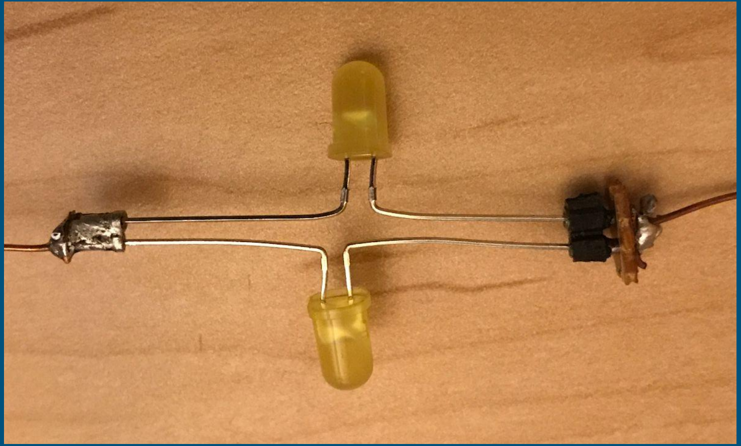


Antenna: Prototype 2



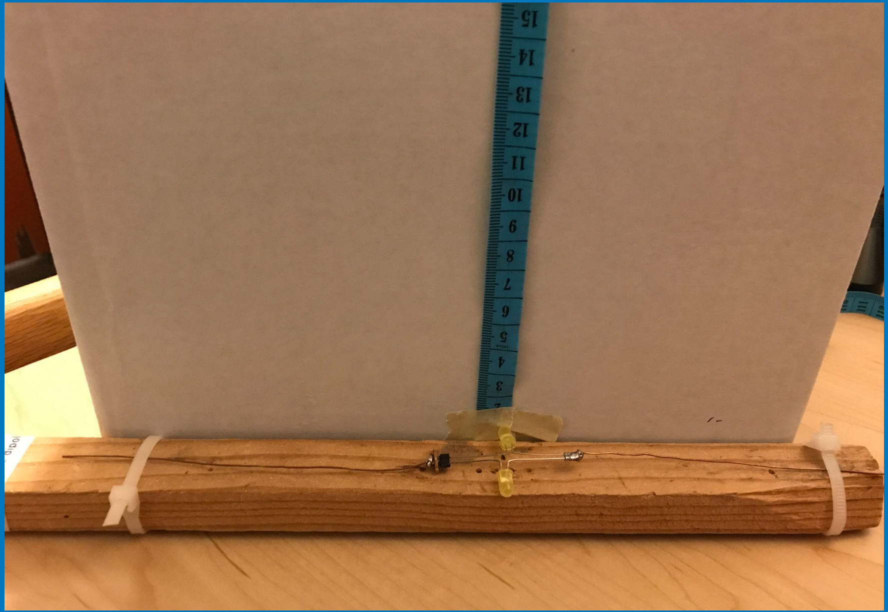
On each side, pin sockets were soldered to the wire – the left ones melted a little :(

The sockets allowed swapping in and out different LEDs.



Experiment A

- Insert LED pair
- Turn off the lights in the room
- Measure the distance between the radio and the antenna when the LED first turns on
- Repeat for all LED colors
- Clip both ends of the antenna by 1 cm (or 0.5 cm)
- Repeat for all lengths



Experiment B

- Insert LED pair
- Turn off the lights in the room
- Begin recording light intensity with the IOLab
- Move the radio closer to the antenna in 1 cm increments
- Repeat for all LED colors

Challenges

Need reproducible signal from the radio.

Solution: use FM modulation, where the total power output is constant.

Want to measure voltage/current: at 441 MHz, the oscilloscope can’t pick it up.

Solution: use LED turn on voltages as a stand in.

Need reproducibility between different LEDs (with different turn on voltages).

Solution: create LED swapping mechanism, so same antenna used for all.

Challenges

Antennas (both receiving and transmitting) are very sensitive. Moving your hand near either (or changing how you hold the radio) can dim the LED.

> Solution: keep the antenna and all surrounding objects fixed, and hold the radio the same exact way for each trial.

RF burns…

> Solution: don’t touch the antenna.

Analysis: Experiment A

Speed of Light: approximately 300,000,000 m/s

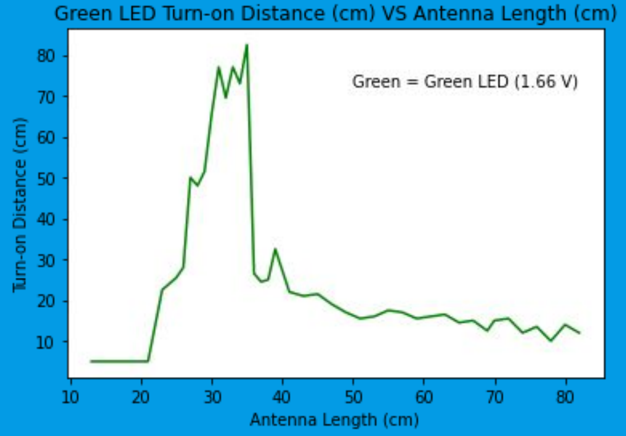
EM Wave Frequency: 441 MHz = 441,000,000 cycles/s

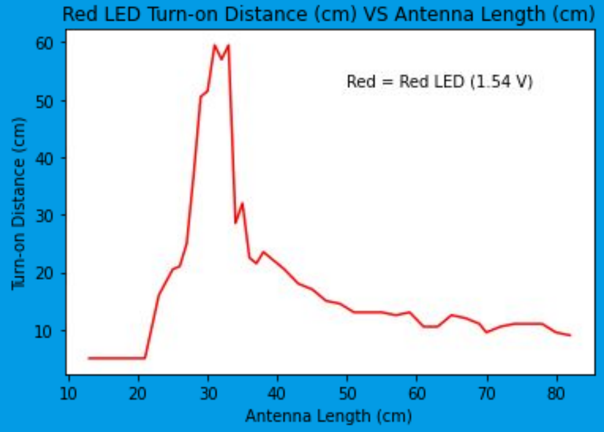
$$v = \lambda f$$

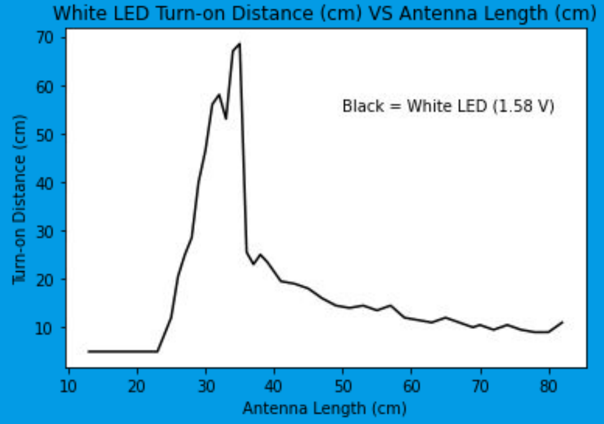
So wavelength is 300 / 441 = ~0.68 m = ~68 cm

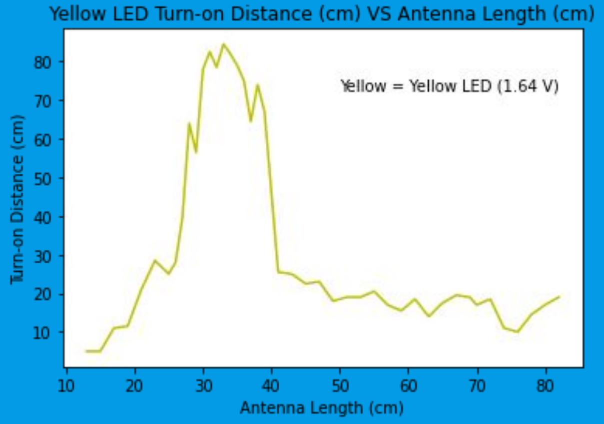
One half wavelength ~34 cm.

Data Collection: Experiment A









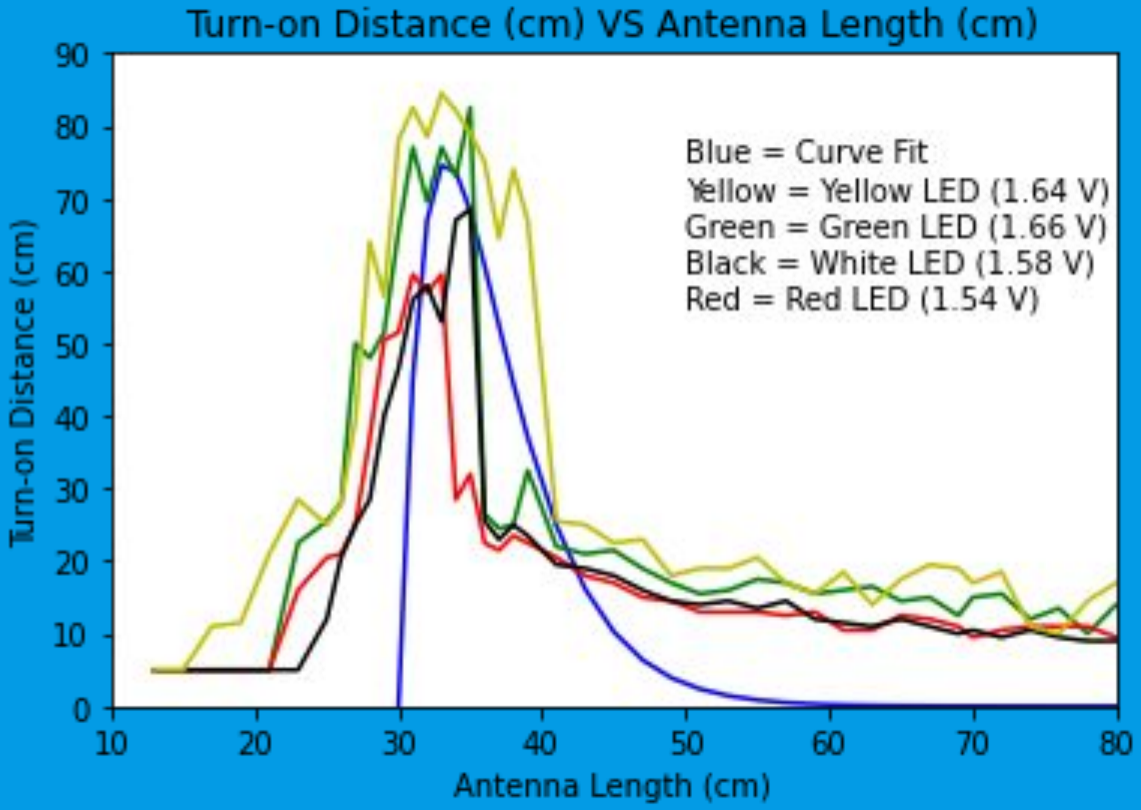
Analysis: Experiment A

E of half-wave dipole

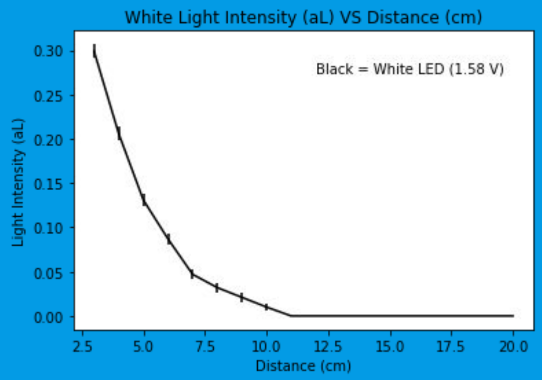
$$E_\theta = \frac{j\eta I_0 e^{-jkr} \cos\left(\frac{\pi\cos\theta}{2}\right)}{2\pi r \sin\theta}$$

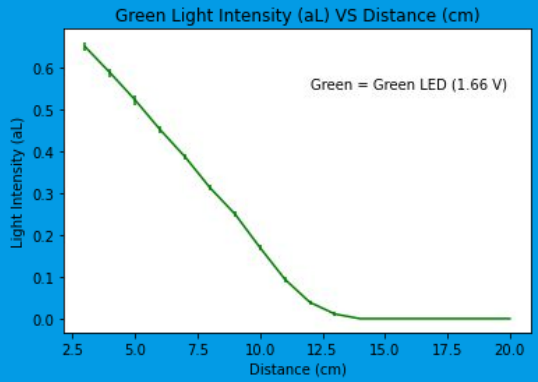
$$h(x) = \frac{c(x-l)}{V * e^{k(x-l)}}$$

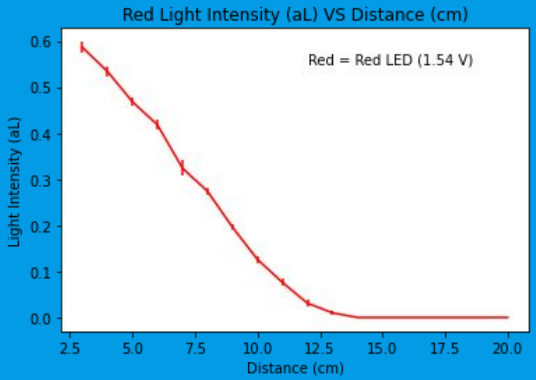
Homemade Model:
c = 100
k = 0.3
l = 30
V = 1.64

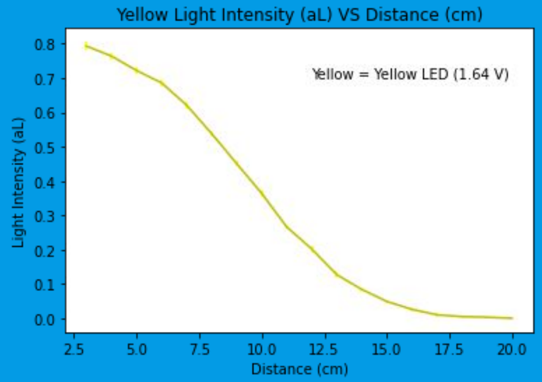


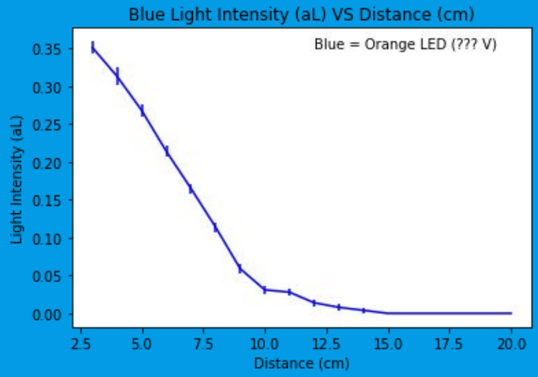
Data Collection: Experiment B







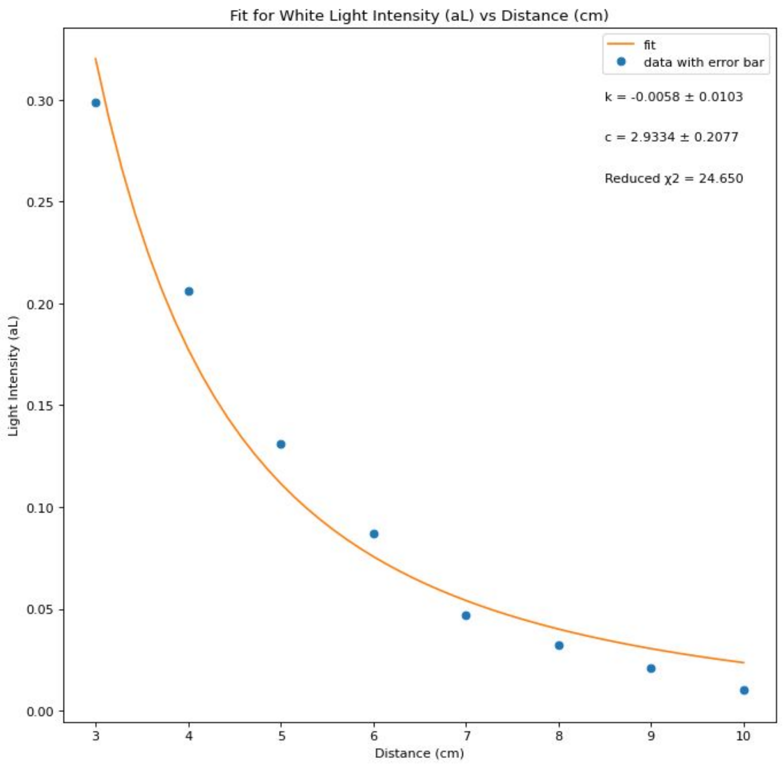


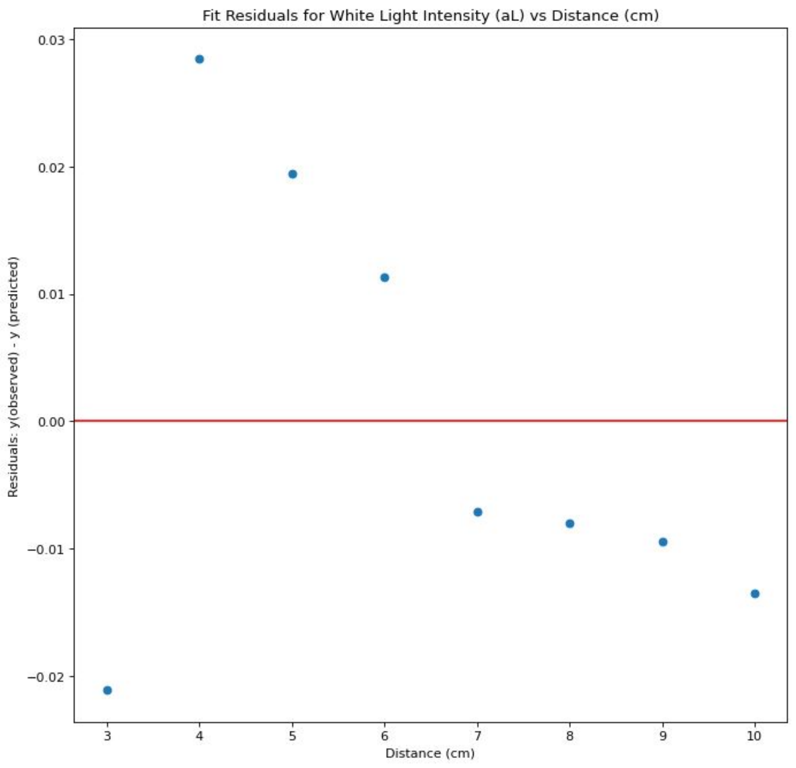


Data Analysis: Experiment B

$$E(r) = \frac{kQ}{r^2}$$

$$L(r) = \frac{k}{r^2} + c$$





Data Analysis: Experiment B

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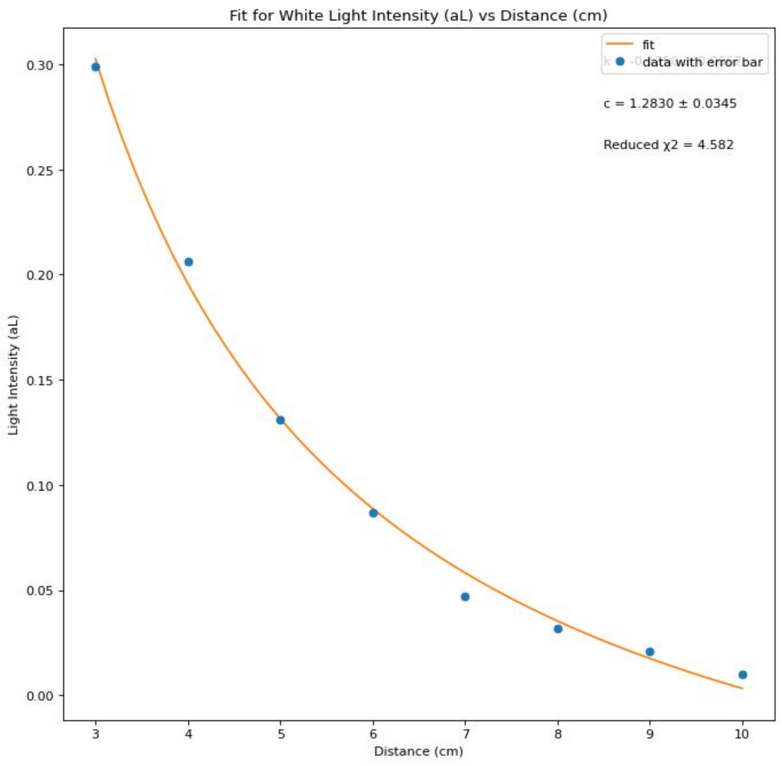

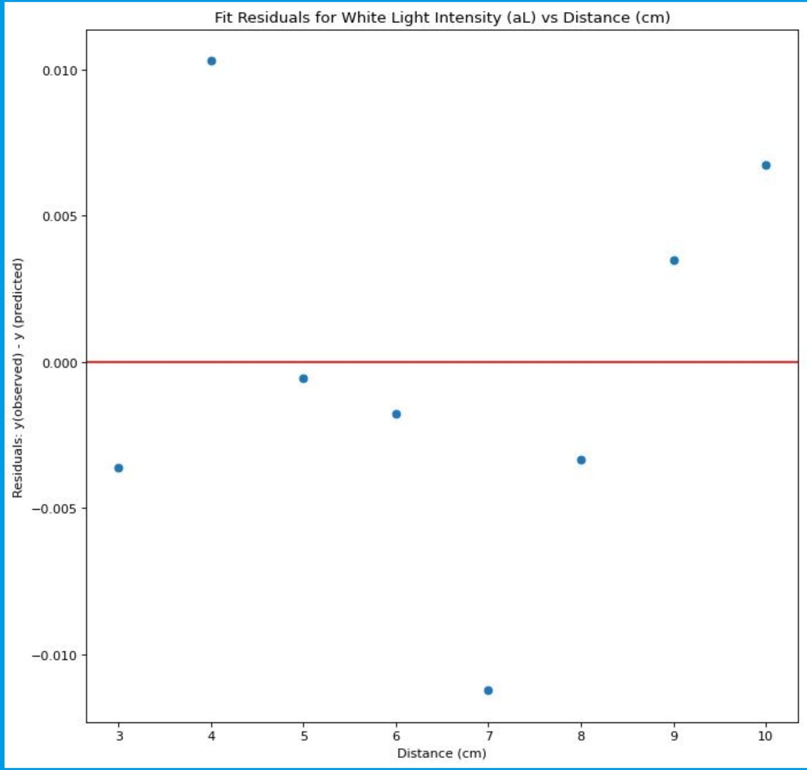

Data Analysis: Experiment B

$$L(r) = \frac{k}{r} + c$$

$$L(r) = \frac{k}{r^2} + c$$

	Slope (1/x)	Turn On Voltage	Slope (1/x^2)	Turn On Voltage
Red	5.970±0.350	1.54 V	26.806±2.552	1.54 V
White	1.283±0.035	1.58 V	2.933±0.208	1.58 V
Yellow	8.118±0.413	1.64 V	50.376±2.812	1.64 V
Green	4.701±0.227	1.66 V	22.884±1.907	1.66 V
Orange	2.261±0.234	N/A	10.774±0.731	N/A

No obvious correlation between ‘slope’ and turn on voltage.

Surprising: expected *some* correlation, even if our fit model was incorrect.

Confounding Variables

LED light intensity doesn’t correlate linearly with voltage or current.

Therefore, while the light intensity correlates with power, it isn’t proportional to it.

Result:

> While our methodology allowed us to get around our hardware limitations, it caused a significant amount of error. Light Intensity vs Distance is interesting, but not the same as Light Intensity vs Power, although the two are correlated.

Future Directions

- Using a directional antenna (such as a Yagi-Uda) on the transmitting radio.
- Using a higher-power radio.
- Using a variable inductor to tune the receiving antenna to other frequencies.
- Trying other receiving antenna shapes (loops, figure eight, etc).
- Inserting the LEDs at different (non-centered) points in the antenna.
- Trying other multiples of half-wavelength antenna (full-wavelength, 3/2, etc).

Future Directions

- Using multicolor LEDs to observe possible shift in color as voltage changes.
- Moving different objects (pencils, wires, magnets, fingers) near the wire.
- Blocking the radio signal with a Faraday cage.
- Use two differently-colored LEDs in the antenna.
- Using a high-frequency oscilloscope (or a network analyzer) to directly obtain voltage/current, rather than the roundabout LED method.

Summary

- Created an antenna and remotely turned on an LED pair - wireless power!
- Determined that an antenna of slightly less than half-wavelength (~34 cm in our case) is the most resonant, for many different voltages.
- Confirmed that LEDs are nonlinear devices.
- Confirmed that power drops off with increasing distance, but were unable to determine whether it followed the inverse square law.
- We were unable to predict the turn on voltage from the light intensity data.

Sources

https://en.wikipedia.org/wiki/Dipole_antenna

https://www.electronics-notes.com/articles/antennas-propagation/dipole-antenna/half-wave-dipole.php

https://www.tutorialspoint.com/antenna_theory/antenna_theory_half_wave_dipole.htm

(Half-Wavelength) Half-Wave Dipole Antenna (antenna-theory.com)