Smartphone-based approach to demonstrating Relativistic Aberration of Light using electronic circuit analogues for undergraduates in the Philippines

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ABSTRACT

Previously, we demonstrated an electronic circuit analogue of one of Special Relativity's (SR) phenomena called the Relativistic Aberration of Light (RAL) (*European Journal of Physics, **42**, 015605, 2021*), which describes the change in the angle an observer sees a light source relative to their direction of motion at relativistic speeds. It used typical bulky laboratory equipment such as (i) function generators, (ii) oscilloscopes, and (iii) power supplies together with our all-pass filter (APF)-based electronic circuit analogue to perform experiments.

In this paper, we present a novel smartphone-based experimental set-up performing the same experiment, but we replace the bulky and expensive laboratory equipment with a low-cost and compact smartphone system that can function as both function generator and oscilloscope. Our smartphone system consists of (i) an Android 8.0 (Oreo) application and (ii) an ESP32-based external module that may be wired or wirelessly interfaced for oscilloscope and signal generation functions.

The setup was able to carry out the experiment, however the sampling rate was only limited to 8.5kHz, but with the added input channel, phase shift calculation was much more consistent, albeit with a slight offset of -15 degrees due to the added buffer circuit between the ESP32 and APF circuit. We hope that through our work, we expand the toolset of physics educators and researchers, particularly those in developing countries, especially with our system's considerations of equipment accessibility, affordability, and simplicity.

Keywords: Physics education, special relativity, circuit analogues, smartphones

1. INTRODUCTION

The analogue approach is a technique where seemingly differing concepts and theories are linked through some shared property or characteristic. This allows complex phenomena to be mimicked through some suitable platform that we refer to as the *analogue system*, which is ideally based on the nature of the phenomenon under consideration (e.g. optical, mechanical, acoustic nature, etc) [1]. This is especially significant for the field of physics since complex phenomena that stem from areas such as special relativity (SR), general relativity (GR), and even in quantum mechanics (QM), are challenging and costly to investigate experimentally. Instead, these phenomena can be simulated through low-cost and low-complexity analogue systems and technology such as our previously reported novel optical analogues. These analogues were capable of simulating different SR phenomena such as the (a) relativistic aberration of light (RAL), (b) Thomas Effect, and (c) Einstein velocity addition (EVA), through the implementation of photonic integrated circuits (PIC). Specifically, we have successfully proven through analytical and experimental methodologies that key parameters in the mechanisms that govern PICs are in fact analogous to certain properties found in the aforementioned SR phenomena [2].

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We also recently reported an electronic analogue of the RAL, which consists of an operational amplifier (OP-AMP)-based cascaded all-pass filter (APF) circuit [1]. This device was initially developed to serve as an educational tool for students across secondary and tertiary schools in the Philippines [1]. While this electronic circuit was proven to be a successful analogue to the RAL, the whole set-up outlined in the experimental procedure of our seminal paper required bulky laboratory equipment such as (i) oscilloscopes, (ii) function generators, and (iii) power supplies [1]. Although these instruments are readily available in some educational institutions in the Philippines, they are lacking in most schools situated in rural areas [3]. This is a considerable limitation for the use of electronic analogues in schools since they lack the necessary equipment.

To address this, we developed the Smartphone Lab or SP Lab, which is a smartphone application that allows the device to function as an all-in-one function generator and oscilloscope. Instead of using bulky laboratory equipment such as the aforementioned function generator and oscilloscope, a smartphone installed with SP Lab can instead be used for our electronic analogue in laboratory experiments. A prototype, which made use of the smartphone's audio jack to perform signal generation and oscilloscope functions, was then presented as a poster at the 2022 Samahang Pisika ng Pilipinas (SPP) Physics Conference. In this paper, we address the limitations found in the development of our prototype, which made use of the smartphone's audio jack for signal generation and oscilloscope functions. Though our prototype was successfully able to replicate the results of our experiments [1], it was limited to only reading signal frequencies within the audible spectrum (20-20kHz) and was vulnerable to artifacts at lower frequencies. To address this, we offload these functions to an external microcontroller unit (MCU) to increase the number of input channels SP Lab can have.

1.1 Smartphone-as-a-Laboratory

In recent literature, numerous smartphone applications have been developed to exploit the devices' built-in features for scientific research. In particular, a few applications such as those developed by the developers of Keuwlsoft and XYZ-Apps were designed to allow a smartphone device to function *either* as a function generator or an oscilloscope. This was achieved by using the smartphone's audio jack—which is typically composed of both a speaker output and a microphone input—to send an electrical signal like a function generator. On the other hand, other applications use the smartphone's microphone input as an oscilloscope to take in acoustic or electrical signals for analysis. Such applications are advantageous for educational and research purposes since smartphones may serve as an alternative laboratory instrument in lieu of more conventional and sophisticated laboratory equipment.

However, repurposing the smartphone's audio jack in this manner posed a limitation. Whereas oscilloscopes generally have two channels for the input and output of a circuit to analyze the behavior of an input signal when passed through a circuit, smartphones typically feature only one input channel through their microphone jacks. Thus the smartphone is capable of measuring the signal only at a single point in a circuit, which is disadvantageous since another point of reference needs to be measured for a more extensive analysis. Moreover, oscilloscopes are capable of measuring a frequency range as broad as 0.01 Hz to 100 MHz. Since the audio jacks of smartphones are ordinarily designed for frequencies in the audible spectrum (20 Hz to 20 kHz), they are not capable of fully replicating the full range of an oscilloscope. From the preliminary assessment of the existing literature on smartphone applications, and to the best of our knowledge, a smartphone application that allows the device to operate as a function generator and oscilloscope *simultaneously* has yet to be developed. Our proposed SP Lab has not only been developed with such functionality, but it also aims to address these limitations, which makes it a viable measuring equipment to perform our RAL circuit analogue experiment.

SP Lab was designed with an external module using the ESP32 microcontroller unit (MCU), specifically the NodeMCU-ESP32s development board. This allows it to accommodate two or more optional input channels by using the MCU's ADC1's multiple input pins. For the RAL experiment, the number of input channels is limited to two, with the signals being sampled with a sampling rate of 8.5kHz. There is also the option of using ADC2 to allow for simultaneous reading of input signals. However, to use ADC2, the MCU's Wi-Fi capabilities must be disabled. For this use-case, we use Wi-Fi to interface the MCU to SP Lab using the WebSocket protocol which allows for real–time data transfer, between the two with the MCU acting as a server, and the smartphone as a client.

The SP Lab application features a GUI where the user can input the desired frequency of the MCU's digital to analog converter (DAC). By pressing run SP Lab's core function loop which can be seen in figure 1.1. The loop starts off with the application generating a WebSocket client using the OkHTTP engine from the Ktor library, here the client looks for the MCU by finding its IP address in the same Wi-Fi network which currently has been hardcoded into the application and MCU source code. After successfully connecting the client then sends a packet to the server containing the specified output frequency of the DAC. The MCU then starts two simultaneous processes, one for outputting a sine wave with a specified signal through the DAC, and one for reading input from the two analog to digital converter (ADC) input pins. The MCU stores data from its ADC into a buffer that is then broadcasted when the client sends a request for the server to send the data. The data for both input channels is sent as one long serial array. Once the client receives the data, it performs a few digital signal processing (DSP) methods namely, normalization for the easy visualization of both input channels and cross-correlation, which is the method used to calculate the phase shift between the two signals.

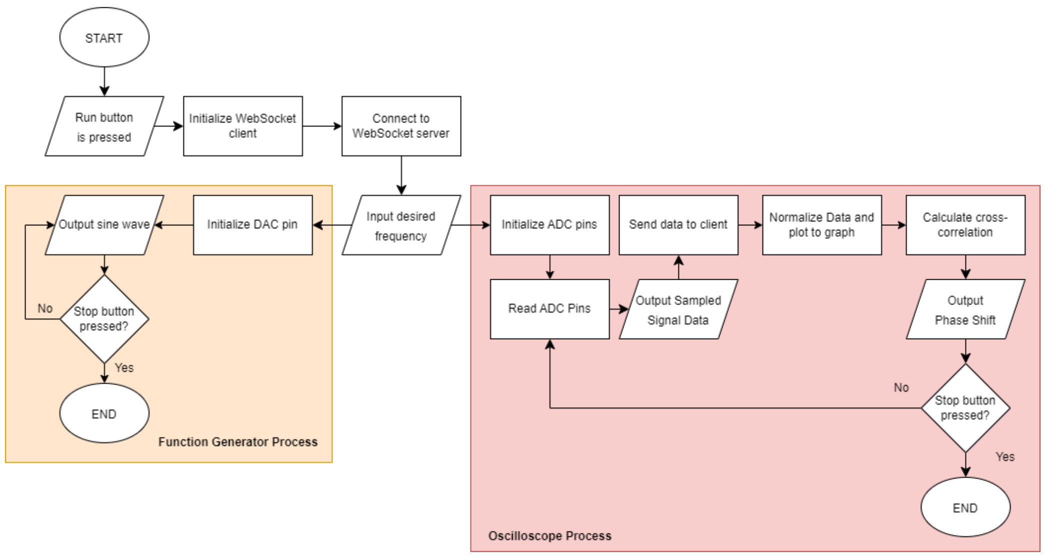

Figure 1.1. Flow chart of SP Lab's function flow

1.2 Relativistic Aberration of Light

The RAL is an SR phenomenon that depicts the change in the propagation of light as observed from two or more inertial frames of reference. In a previous work, we derived a mathematical expression that describes the RAL using Einstein's velocity addition (EVA); this expression is referred to as the directional angle Ψ, which represents the angle at which the relativistic aberration is visible to an observer. This is shown in Fig. 1.2, which depicts the following scenario: firstly, an observer A—who resides in an initial rest frame Σ—observes a ray of light at an angle Ψ from a light source C located at a reference frame Σ''. We note that observer A measures the light emanating from C to be traveling at a relativistic velocity $\bar{V}_1 \oplus \bar{V}_2$. Secondly, another observer B—who is traveling at a velocity $\bar{V}_1$ in its own reference frame Σ'—observes the same light emitted by C to be traveling at a velocity of $\bar{V}_2$ at an angle θ_2 (for simplicity we assume Σ' is moving parallel to Σ along an arbitrary positive coordinate axis such that $\theta_1 = 0$, and $\theta_2 = \theta$).

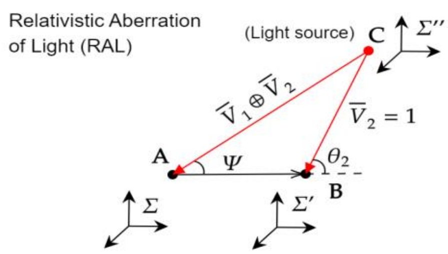

Figure 1.2. Relativistic aberration of light along with EVA

For simplicity, we will omit a detailed discussion on our previous derivation of the mathematical expression for the directional angle Ψ as it a long and complex process, and we instead encourage our readers to refer to our original work [1]. In summary however, we can simply note that by reversing the directions of $\bar{V}_1$ and $\bar{V}_1 \oplus \bar{V}_2$, as well as setting $\bar{V}_2 = 1$ as the speed of light c, the EVA operation may now be applied. Thus, we can we express Ψ as a function of the relativistic velocity $\bar{V}_1$ and frequency F, which has the following expression.

$$\Psi(V_1, F) = -2\tan^{-1}\left[2\pi F \frac{(1-V_1)}{(1+V_1)}\right]. \quad (1)$$

1.3 Original experimental set-up of the RAL circuit analogue

As mentioned previously, we developed an electronic analogue for the RAL based on a two-stage APF circuit [1], whose circuit schematic is shown in Fig, 1.3(a). The phase response of the electronic analogue's output signal is given in Eq. 2, where *F* is the input frequency of the electronic analogue circuit and *RC* is the time constant. It can immediately be noted that Eq. 1 has a similar form to Eq. 1, and so both expressions were simply equated using the relationship shown in Eq. 3. This implies that the phase response of the electronic analogue is therefore analogous to the directional angle of the RAL.

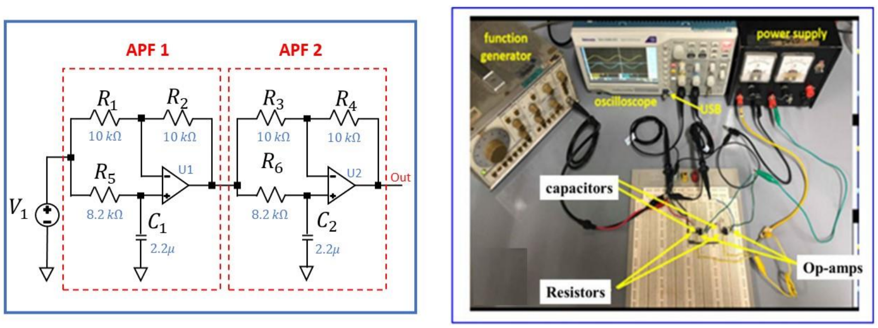

Figure 1.3. Schematic diagram of the electronic analogue (Left) and its equivalent experimental set-up (Right).

$$\Phi = -2\tan^{-1}[2\pi FRC]. \quad (2)$$

$$RC = C\frac{1 - V_1}{1 + V_1}. \quad (3)$$

The original experimental set-up of the electronic analogue is shown in Fig. 1.3, where the actual circuit (built on the electrical breadboard) is attached to various laboratory instruments including a function generator, a digital oscilloscope, and a power supply. Although we have demonstrated that this set-up can mimic the RAL in terms of the phase response Φ of the circuit's output signal, it still requires bulky, sophisticated, and costly equipment such as the aforementioned laboratory instruments. In this regard, our SP Lab application can alleviate this issue since students or researchers can simply use their smartphones as an all-in-one function generator and digital oscilloscope.

2. EXPERIMENTAL SET-UP FOR SP-LAB

To investigate the viability of SP Lab, we first replicated the original experimental set-up shown in Fig. 1.3(b), where we replace the function generator and digital oscilloscope with the smartphone with the SP Lab application installed. We also replace the power supply with two conventional 9V batteries powering the OP-AMPs in the circuit (see Fig. 2.1(c)). The whole experimental set-up has a slight modification, where we introduce a third OP-AMP component (see the circuit schematic shown in Fig. 2.1(b)).

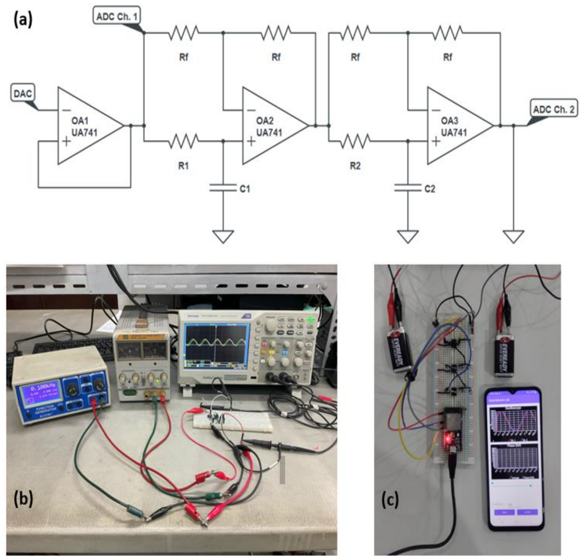

Figure 2.1. (a) APF circuit schematic (b) Conventional experimental setup. (c) SP Lab experimental setup.

For this experiment, introduce we arbitrarily set $V_1 = 0.99$ and $C = 0.03$ to shift the phase response of the APF circuit to the left, which will allow us to experiment with higher values for V1 at lower frequencies. The calculated RC value is then equal to 1.508e-4. We note that the resistor and capacitor values are as follows: $R_1 = R_2 = 75\,\Omega$, and $C_1 = C_2 = 2.2\,F$. We then perform three experiments using both a conventional set-up similar to the one shown in Fig. 1.3 and our modified set-up using the smartphone with SP Lab (see Fig. 2.1(c)), where we varied the input frequency from 130 Hz, 400 Hz, to 970 Hz, which correspond to -30 deg, -90 deg, and -180 deg of phase shift respectively. We then measure the observed phase shifts and see how they compare compared to the theoretical phase shifts.

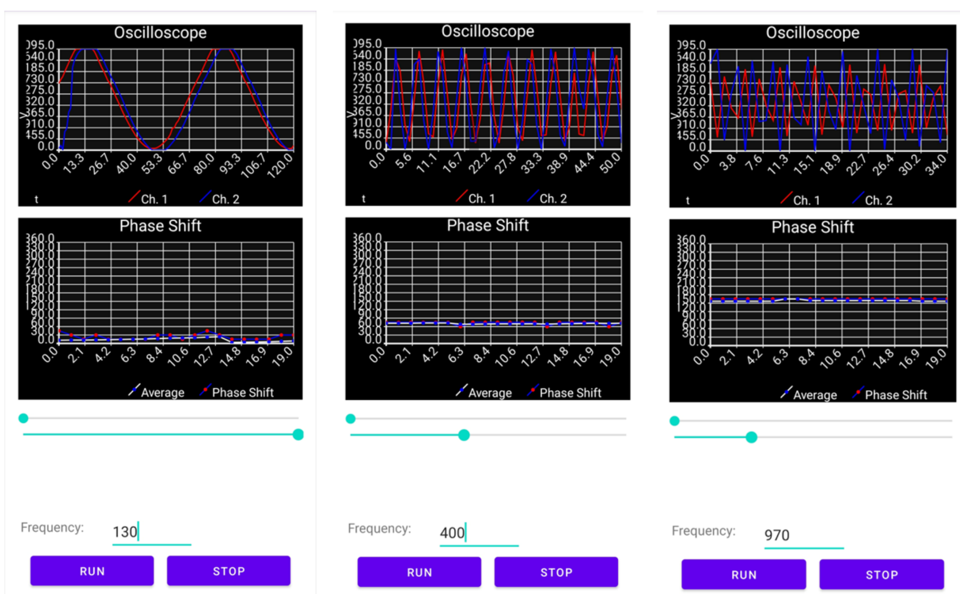

Figure 2.2. Screenshots of SP Lab for (a) $F = 130$Hz, $\phi \approx 15^\circ$, (b) $F = 400$Hz, $\phi \approx 75^\circ$, (c) $F = 970$Hz, $\phi \approx 165^\circ$

It can be seen from screenshots SP Lab (which were taken during the experiment) that SP Lab was both able to sample two input channels and determine the phase shift between the two signals while working wirelessly between the app and the MCU. However, the calculated phase shift had a consistent offset of 15 degrees, which is possibly due to the buffer stage added between the MCU and the APF circuit's input. It can also be observed that at higher frequencies the read signals became more jagged, and at times seemed as if there were aliasing issues, which are both signs of an insufficient sampling rate. It seems that at higher frequencies the sampling rate decreased, this is due to more resource being allocated to the DAC, thus decreasing the ADCs performance and making it seem as though the signals were experiencing aliasing. At a frequency $F = 970\,Hz$, it can be observed that the signals begin to approach the Nyquist rate, but as it still returns a consistent yet offset phase difference, we determine that the sampling rate is still sufficient. This is because the phase difference which is the result of performing cross-correlation between the two signals is dependent on the assumed sampling rate. A wrong assumption will result in a wrong calculated phase shift, while an inconsistent sampling rate would show in an inconsistent phase shift.

3. CONCLUSION

In this paper, we were able to successfully develop a smartphone and ESP32 system to serve as an alternative to traditional laboratory equipment such as function generators and oscilloscopes. We were then able to use this system to perform our RAL experiment without the need for any laboratory equipment. Though the system showed it had an offset of -15 degrees, due to its consistency and predictability we can simply introduce a correction bias of +15 degrees to make up for this offset. However, this would only be true for the experimented frequency range. More work also must be done to improve the sampling rate of the oscilloscope functions of the system to allow for experiments past the range done in this paper. With this, we show the capability of smartphones to act as a low-cost alternative to laboratory platforms to allow institutions which don't have access to this traditional laboratory equipment to perform physics and circuit experiments similar to our RAL experiment to undergraduate level students. With further improvements a low-cost learning module featuring our developed circuit analogues and SP Lab could be distributed to remote areas, thus making performing Physics education and demonstrations much more accessible.

4. ACKNOWLEDGEMENTS

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