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Earth Gravity Detection System with Altitude Variations Using Phypox Application Integrated with Smartphone Acoustic Sensors

Rio Sebastian[1*], Suparno[2], Puji Hariati Winingsih[3], Handoyo Saputro[4], Nadya Amalia Putri Hapsari[5]

[1,2,5]Department of Physics Education, Yogyakarta State University, Indonesia
[3,4]Department of Physics Education, Sarjanawiyata Tamansiswa University, Indonesia
[3]Department of Science Education, Yogyakarta State University, Indonesia
[4]Department of Physics Education, Malang State University, Indonesia

**Corresponding Address: riosebastian.2022@student.uny.ac.id*

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ABSTRACT

This study aims to examine the effect of altitude on the acceleration of gravity with the help of smartphone acoustic sensors. The altitude varies from the interval 100-1061 MASL (Mean Above Sea Level), located around the Special Region of Yogyakarta. An iron ball is dropped from a certain height, and the time it falls is observed using an acoustic sensor in Phypox, and the results are used to determine the acceleration value due to gravity (g) through the equation $g = 2h/t^2$. Fitting data from measurements of the four altitude variations are shown in the polynomial equation $y = 0.000003x^2 - 0.0035x + 10.718$ m/s^2 with a regression number R^2 = 1,000. This equation shows that the acceleration value due to gravity will decrease quadratically with each increase in the altitude per meter above sea level.

INTRODUCTION

The influence of the acceleration of gravity of the Earth is inseparable from the activities of living things, which give the effect of a pull perpendicular to the center of the Earth so that it is necessary to measure the acceleration of gravity of the Earth. The scalar value of the gravitational acceleration field is a parabolic function between the displacement and time variables (White et al., 2007). Based on metrology, gravitational acceleration influences force measurements involving force standards such as measurements in mechanics, electricity, and fluid dynamics (Marson & Faller, 1986). The importance of measuring the Earth's gravitational acceleration in human activities, for example, in aircraft flight fields which are used to evaluate the accuracy and spatial resolution of the Earth's gravitational field and satellite navigation systems on aircraft (Hwang et al., 2012; Koneshov et al., 2015; Ménoret et al., 2018; Sokolov et al., 2016). In addition, in the economic field, the activity of measuring the weight (weighing) of an item to be sold, it is known that the weight value is affected by the value of the acceleration of the Earth in a place so that there will be differences in price and weight depending on the altitude of the place (Rinanthy et al., 2016). Earth's gravitational acceleration measurement data helps seismic data to understand the structure of the Earth so that it supports geological work (Dove et al., 2010; Masson et al., 2012; Xia et al., 1994). In the field of biology, gravitational fields have an impact on physiological adaptations in humans so that they affect human survival (Goswami et al., 2021). A study by Salim et al. (2022) stated that measurements of the acceleration of gravity could be considered in the development field when designing building designs and in agriculture to select plants that follow the value of the acceleration of gravity in a place. Therefore, the benefits of measuring the value of the Earth's gravitational acceleration can support human life activities, so an accurate and practical measurement method is needed.

Previous scientists have carried out experiments on measuring the acceleration of gravity. However, they still use simple and manual equipment, so there are often measurement errors and inaccuracies. The methods of measuring the acceleration of gravity that are often used are mathematical pendulums, vibrations on springs, Atwood planes, and free fall motion (Elot et al., 2022; Pili et al., 2018; Rinanthy et al., 2016). In addition, measurements of gravitational acceleration in several previous studies included using a physical pendulum projectile(R., 2014), analysis of a video tracker application (Afifah et al., 2015), internal accelerometer (Vogt & Kuhn, 2012), microphone on a device (Khairurrijal et al., 2012), application-based laboratory logger pro (Nurullaeli & Astuti, 2018), measurements with mobile phones that operate with electro-mechanical system sensors (Kittiravechote & Sujarittham, 2020; Kuhn, 2014; Kuhn & Vogt, 2013; Pili et al., 2018), ticker timer (Fontana et al., 2020), manipulating cold atoms (Ferrari et al., 2006; Peters et al., 1999; Poli et al., 2011), using an atomic interferometer (Hauth et al., 2013; Mc Guirk et al., 2002; Peters et al., 2001; Snadden et al., 1998), and a mechanical pendulum with an electronic system (Usayidah & Rahmawati, 2015). Galileo Galilei originally carried out the experiment to find the value of the Earth's gravitational acceleration in 1602 and expressed the acceleration of gravity with a mathematical pendulum (Delti, 2022). In his mathematical pendulum experiment, Galileo noticed that if released simultaneously from rest, all objects tend to land simultaneously, concluding that the fall time does not depend on the object's mass (Lo, 2011). In the experiment of measuring the gravitational acceleration using the mathematical pendulum method, errors often appear when determining the pendulum's angle, which is inconsistent and too large so that $\sin \theta = \theta$ does not apply. In addition, there is a damping force (air resistance) on the swing, which causes a longer time will slow down. It causes the data to be inappropriate and inaccurate (Aisiyah et al., 2022; Elot et al., 2022). A digital and automatic method and system for measuring the acceleration of gravity using the latest technology is needed to reduce the error rate and increase the accuracy of time measurements.

Current technological developments make it easier for humans to carry out all activities, especially in the development of today's smartphones, which have increasingly sophisticated features and applications easily utilized by users. Most smartphone devices have embedded several sensors, including acoustic (microphones), accelerometer, strong magnetic field, light, and gyroscope sensors (Kuhn & Vogt, 2013; Suciarahmat & Pramudya, 2015). These sensors support the work of smartphone sophistication in facilitating user activities, one of which is the use of acoustic sensors on smartphones that can be used to measure the value of the acceleration of gravity accurately and practically (Abellán-García et al., 2012; Anni, 2021; Kittiravechote & Sujarittham, 2020, 2021; Schwarz et al., 2013). In physics experiments, smartphone sensors-based experiments on Phypox direct students to do real and independent practicums to motivate students to explore physics experiments (Mayampoh et al., 2021; Nanto et al., 2022; Sebastian et al., 2018). Phypox can collect students' real-time experimental data remotely (Nanto et al., 2022; Staacks et al., 2022). The Phypox application connects students to smartphone sensors more practically and effectively (Carroll &

Lincoln, 2020). Smartphone relationships with students who are meaningful in learning physics can develop digital and cooperative problem-solving skills (Pusch et al., 2021). The use of the Phypox application on smartphone acoustic sensors helps teachers. It provides good responses for students to carry out simple free fall experiments with accurate and practical accuracy both at school and in the surrounding environment (Kittiravechote & Sujarittham, 2021; Saputro et al., 2022). Bara et al. (2021) recommend acoustic smartphone sensors via the Phypox application as a precise and accurate measurement of gravitational acceleration.

However, in several previous studies using smartphone sensors through a mathematical pendulum experiment using the Phypox integrated accelerometer sensor, the results of the acceleration of gravity were 9.73 m/s^2. This measurement was inaccurate because it did not use a remote control (Suciarahmat & Pramudya, 2015). Meanwhile, better measurement results were obtained in the research of Fatmala et al. (2019) with a simple pendulum learning using the Phypox application. The average acceleration of gravity with an accuracy of 98.6% is 9.87 m/s^2. In research, Bara et al. (2021) analyzed that measuring the acceleration of gravity using the Phypox application with the free fall method provides a value for the acceleration of gravity in line with theory, namely the range between 9.8 m/s^2 to 10 m/s^2. Developing a free fall motion experiment using a smartphone in the Phyphox application shows validity and reliability in a good category when used in practicum (Walid & Umar, 2022). By measuring the acceleration of gravity through the Phypox smartphone sensor, it can provide practicality and economic value because it can be done anywhere without being limited to laboratory equipment (Kittiravechote & Sujarittham, 2020). However, several previous studies have not yet implemented the measurement of gravitational acceleration under the influence of altitude over a large range. This was shown in the research by Subhan et al. (2022), who measured the acceleration of gravity using the free fall motion method with variations in altitude in the range of 15-273 MASL and obtained a graphical determinant index value of 0.65 in the medium category. Therefore, in this study, a factor of the acceleration of gravity based on the altitude of a place with a greater range and better accuracy will be tested through a measurement system for measuring the acceleration of gravity using a smartphone acoustic sensor integrated with the Phypox application. Based on several problems and supported by the theory of determining free fall motion, this study aims to examine the effect of altitude on the value of the acceleration of gravity with the help of smartphone acoustic sensors integrated into the Phypox application.

METHODS

Based on classical mechanics theory, the value of acceleration due to gravity is influenced by several factors. In his theory, Sir Isaac Newton concluded that each region has a different gravity acceleration value, but when averaged, the value shows 9.831302275 m/s^2 (Rosdianto, 2017). This statement explains Newton's law of universal gravitation which has a solution to the problem of the value of the acceleration due to gravity, as shown in Equation 1.

$$F = m_2 . g = G\frac{m_1 m_2}{r^2} \quad (1)$$

In Equation 1, it is known that the value of F is Newton's gravitational force, the value of g is the acceleration of gravity, G is the value of the gravitational constant of 6.67 x 10^{-11} Nm^2/kg^2, m1 is the value of the mass of the Earth by 5.98 x 10^{24} kg, m^2 is the value of the mass of objects that is dropped, and **r** is the value of the distance from the source of gravity to a point which in the case of this study is the sum value of the Earth's radius (R_{earth}) which is 6.371 x 10^6 m with the altitude (**dr**).

In Equation 1, by eliminating the value of the object's mass (m2), the value of the acceleration due to gravity can be determined through Equation 2.

$$g = G\frac{m_1}{r^2} \quad (2)$$

Equation 2 is consistent with previous studies, which stated that the difference in the value of the acceleration due to gravity is influenced by the altitude factor, where the higher a place is above sea level, the value of the acceleration due to gravity will decrease (Firdaus et al., 2019).

This research was conducted using an experimental method using a gravitational acceleration detection system using a smartphone acoustic sensor integrated with the Phypox application with the research flowchart shown in Figure 1.

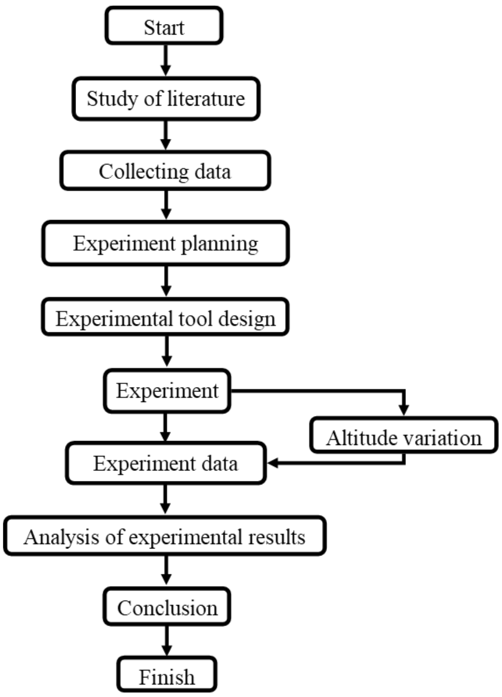

Figure 1. Research flow chart

In this study, the technique of collecting data using the concept of free fall motion was carried out by five variations of location altitude, namely 100 MASL, 298 MASL, 650 MASL, 871 MASL, and 1061 MASL where each location consisted of five variations of falling object heights of 1.1 m; 1.0 m; 0.9 m; 0.8 m; and 0.7 m. The locations chosen for this research are Yogyakarta City and Sleman Regency. The selection of the location was considered because the location has varying altitudes. The researchers determined the altitude of a place using a smartphone through the mapcoordinates.net application. The research was conducted on 16 and 23 October 2022. The tools and materials used were statives, iron balls, smartphones that had integrated the Phypox application, and a set of electromagnetic modules connected to a buzzer. The design of the tools used in the research can be seen in Figure 2.

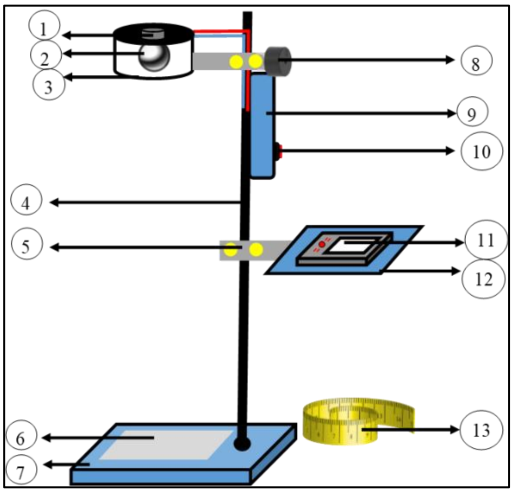

Figure 2. Design of Earth's Gravity Acceleration Detection System

Information:
1. Electromagnets
2. Iron Ball
3. PVC Pipe
4. Stem Stative
5. Stative Clamp
6. Plate Zn
7. Stative Ballast
8. Buzzers
9. Electromagnet Voltage Source Circuit Box
10. Button electromagnetic module
11. Smartphone
12. Iron Plate
13. Meter Tape

The working mechanism of this method is that the iron ball is dropped by pressing a button electromagnetic module to cut off the electricity to the magnet while sounding a buzzer as a start response on the stopwatch acoustic sensor in the smartphone until the iron ball touches the zinc (Zn) plate below as a stop response on the stopwatch. The mechanism is similar to the method using a super ball in which the sound produced by the ball impacts is recorded with a microphone as a voltage signal over some time, resulting in a chronological sequence of super balls, with the sound created by the impacts producing very sharp peaks (Aguiar & Laudares, 2003; White et al., 2007). In measuring the gravitational acceleration with this method, the falling time of the object (t) and the height of the object falling have been adjusted by five variations of height (h) so that the acceleration of gravity can be determined through Equation 3.

$$g = \frac{2h}{t^2} \quad (3)$$

In the process of retrieving data from the measurement of the acceleration of gravity, the researcher set the threshold (as the amplitude threshold setting for the sound to be read) and set the minimum delay (as the minimum time it was read in response) and obtained the value of the time the object fell whose appearance is shown in Figure 3, so that the analysis the data by using Equation 3, the value of the acceleration due to gravity is obtained.

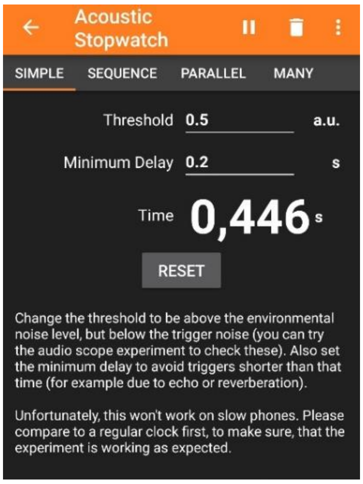

Figure 3. Phypox application interface in measuring falling objects

In Equation 3, because there is a time correction caused by the sound reaching the acoustic smartphone sensor with the average speed of sound in the air (v) at the time of measurement (t) so the actual time ($\bar{t}$) must be subtracted by the time correction value (Δt) as shown in Equation 4.

$$\bar{t} = t - \Delta t \quad (4)$$

The time correction value (Δt) in Equation 4 can be obtained using the equation for the speed of sound in air shown in Equation 5

$$\Delta t = \frac{h}{v} \quad (5)$$

In Equation 5, it can be seen that h is the value of the height of the falling object, and v is the value of the average speed of sound in air at 20 °C of 343 m/s^2 (Halliday et al., 2010).

After the data is obtained for the acceleration due to gravity based on the altitude value, the data is processed into Ms. Excel to make it easier to find the average value obtained for each variation in altitude which is then presented with a polynomial regression graph so that the regression equation is shown in Equation 6 (Meyer & Avery, 2009; Ose, 2016).

$$y = ax^2 + bx + c \quad (6)$$

The y-value is the dependent variable (the acceleration value due to gravity), and the x-value is the independent variable (altitude value).

RESULTS AND DISCUSSION

The workings of the Earth's Gravity Acceleration Detection System tool using a smartphone acoustic sensor integrated with the Phypox application can be written as follows:

1. Prepare the Phypox application on a smartphone and set the minimum delay and threshold according to the size of the sound disturbance in a measurement area, as shown in Figure 4

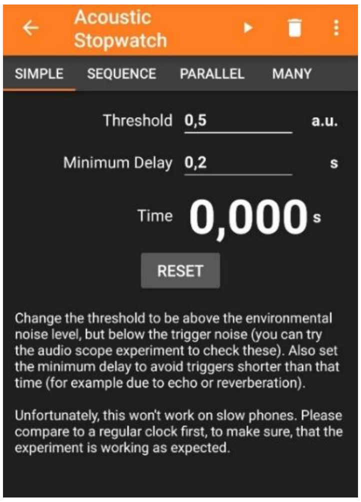

Figure 4. The initial display of the Phypox application on a smartphone

2. Start activating the stopwatch in the Phypox application by pressing the play button to change to an icon in a red circle, and the smartphone is ready to be used for time measurement, as shown in Figure 5.

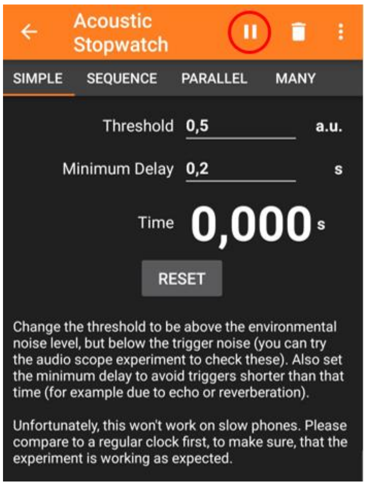

Figure 5. The Phypox application display is ready to take time measurements

3. Pressing the button on the electromagnet module so that the electric current in the magnet is cut off and the iron ball falls together with the buzzer sound, which is detected by the microphone on the smartphone as a start response, as shown in Figure 6.

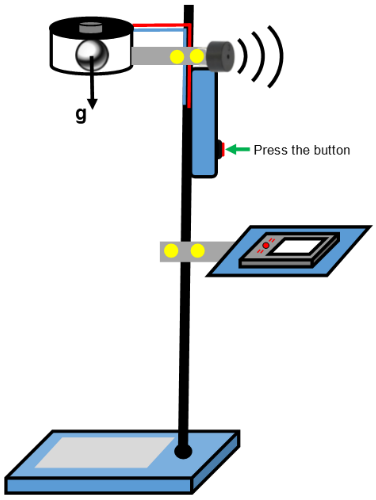

Figure 6. Stages of pressing the electromagnetic module button

4. The iron ball falls freely, and the stopwatch on the smartphone runs until it detects a second sound, as shown in Figure 7.

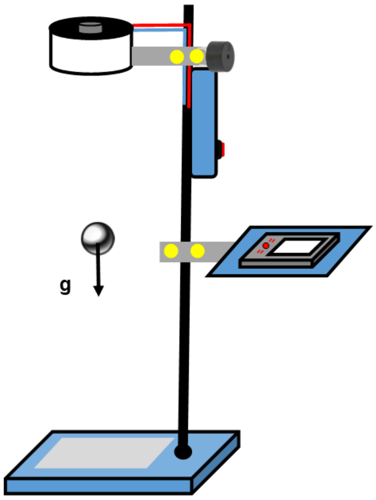

Figure 7. The stages of the falling iron ball and the smartphone stopwatch running

5. When the iron ball reaches the bottom, it hits the Zn plate resulting in a loud sound that detects the second sound as a stop response to measuring time in a smartphone, as shown in Figure 8.

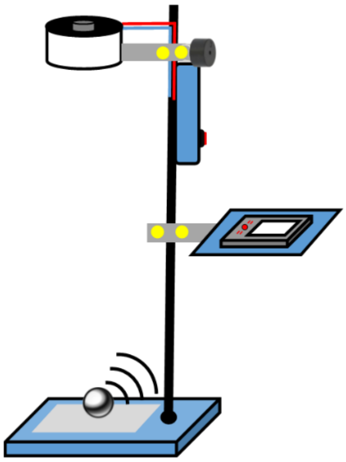

Figure 8. Stages of the iron ball touching the Zn plate

6. The time it fell on the iron ball was measured in the Phypox application stopwatch on the smartphone, as shown in Figure 9.

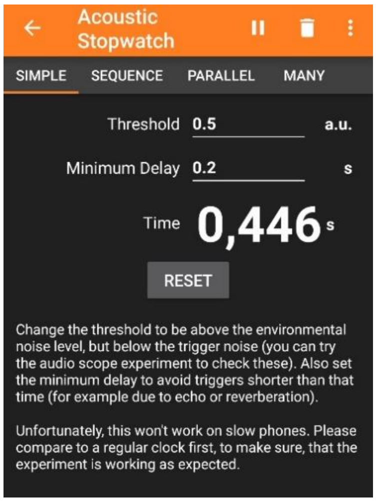

Figure 9. Display of the Phypox application on a smartphone after measuring the time the ball fell

Based on the research that has been done, the results of measuring the acceleration of gravity with variations in the altitude of each location using the smartphone acoustic sensor integrated with the Phypox application are shown in Table 1.

Table 1. Gravity Acceleration Measurement Results

No	*Altitude* (MASL)	Falling height (m)	Time (s)	Gravity Acceleration (m/s^2)	Average Gravity Acceleration (m/s^2)
1	100	(0,7 ± 0,0005)	0,362	10,698	10,398
		(0,8 ± 0,0005)	0,406	9,684	
		(0,9 ± 0,0005)	0,412	10,585	
		(1,0 ± 0,0005)	0,446	10,051	
		(1,1 ± 0,0005)	0,448	10,972	
2	298	(0,7 ± 0,0005)	0,383	9,566	9,925
		(0,8 ± 0,0005)	0,407	9,675	
		(0,9 ± 0,0005)	0,424	10,014	
		(1,0 ± 0,0005)	0,440	10,308	
		(1,1 ± 0,0005)	0,468	10,062	
3	650	(0,7 ± 0,0005)	0,384	9,506	9,619
		(0,8 ± 0,0005)	0,406	9,713	
		(0,9 ± 0,0005)	0,433	9,619	
		(1,0 ± 0,0005)	0,458	9,548	
		(1,1 ± 0,0005)	0,476	9,710	
4	871	(0,7 ± 0,0005)	0,383	9,546	9,776
		(0,8 ± 0,0005)	0,400	10,007	
		(0,9 ± 0,0005)	0,431	9,673	
		(1,0 ± 0,0005)	0,457	9,573	
		(1,1 ± 0,0005)	0,467	10,079	
5	1061	(0,7 ± 0,0005)	0,384	9,496	9,448
		(0,8 ± 0,0005)	0,408	9,599	
		(0,9 ± 0,0005)	0,440	9,307	
		(1,0 ± 0,0005)	0,458	9,539	
		(1,1 ± 0,0005)	0,486	9,299	

The measurement results in Table 1 are the average result of measuring the time for each height of the fall from five repeated measurements and the time that has been reduced by the correction time (Δt) in Equation 4. This time correction occurs because sound takes time to reach the sensor. It doesn't arrive instantly. Using the speed of sound 343 m/s, the time correction value for each height can be shown in Table 2.

Table 2. Gravity Acceleration Measurement Results

No	Height of Falling Objects ***h*** (m)	Time Correction Δ***t*** (s)
1	(0,7 ± 0,0005)	0,0020
2	(0,8 ± 0,0005)	0,0023
3	(0,9 ± 0,0005)	0,0026
4	(1,0 ± 0,0005)	0,0029
5	(1,1 ± 0,0005)	0,0032

In Table 1, for a clearer interpretation of the results of the measurement of the acceleration due to gravity, it can be shown in Figure 10.

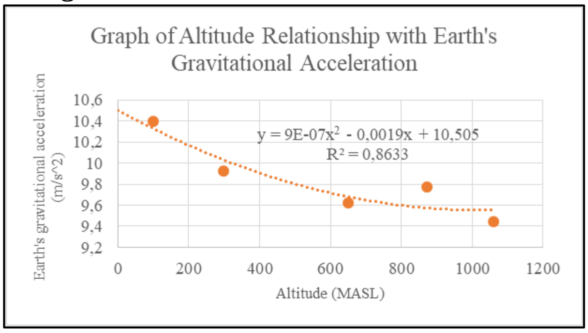

Figure 10. Graph of the relationship between the acceleration of gravity and the altitude of a place

Based on the interpretation of the graphic measurements in Figure 10, it can be seen that the graph lines form a second-order polynomial regression line, which, as the altitude increases, shows a quadratic decrease in the value of the acceleration due to gravity with the equation $y = 0.0000009x^2 – 0.0019x + 10.505$, with the regression coefficient reaching $R^2 = 0.863$ which is included in the very strong correlation category. In this equation, y is the value of the Earth's gravitational acceleration, while x is the altitude of the observation location (altitude). This is consistent with the equation of Newton's law of universal gravitation shown in Equation 3. The results of measuring the acceleration of gravity in this study are also in harmony with the research of Subhan et al. (2022), which states that the higher a place is from the surface (MASL), the smaller the influence of the acceleration of gravity on an object.

The measurement data based on the height at 100 MASL, which is located at latitude -7.8081 and longitude 110.3820 (Yogyakarta City), obtained the acceleration of gravity of 10.398 m/s^2, at 298 MASL, which is located at latitude -7.6982 and longitude 110, 4145 (Sleman Regency) obtained an acceleration of gravity of 9.925 m/s^2, at 650 MASL (Sleman Regency) which is located at latitude -7.6237 and longitude 110.4261 (Sleman Regency) obtained acceleration of gravity of 9.619 m/s^2, at 871 MASL which is located at latitude -7.6029 and longitude 110.4605 (Sleman Regency) obtained an acceleration of 9.776 m/s^2 and at 1061 MASL which is located at latitude -7.5877 and longitude 110.4560 (Sleman Regency) obtained an acceleration of gravity of 9.448 m/s^2. These data are consistent with the research of Martini & Oktova (2009), which states that the value of the acceleration of gravity in the city of Yogyakarta is, on average (9.76 ± 0.07) m/s^2. While in general, the data obtained are in harmony with the research of AbdElazem & Al-Basheer, (2015) which obtained a value of g = (9.8092 ± 0.0384) m/s^2 with an error of 0.193% and research by Abellán-García et al., (2012) with the acquisition g value = (9.796 ± 0.003) m/s^2. In theory, the value of the gravitational acceleration can be determined when it is at a location altitude of 0 MASL so that the value of **r** is the radius of the Earth by using Equation 3. It is known that G is the value of the gravitational constant of 6.67 x 10^{-11} Nm^2/kg^2, m_1 the value of the Earth's mass is 5.98 x 10^{24} kg Earth radius (R_{earth}) which has a value of 6.371 x 10^6 m so that the magnitude of the acceleration due to gravity is obtained g = 9.826 m/s^2. However, it can be seen in Figure 13 that the value of the Earth's gravitational acceleration at an altitude of 1061 MASL deviates far from the fitting curve, so we decided to exclude this data from the analysis. This is because, at an altitude of 1061 meters above sea level, there is a friction factor from the air greater than the height below it. In addition, the factor of wind noise and the measurement location at 1061 MASL influences the acoustic sensor, so the response from the acoustic sensor is inconsistent. Only four pieces of data are analyzed in the next paragraph.

The fitting curves for the four data are shown in Figure 11. The four data fitting curves excluding data at the height of 1061 MASL produce a regression equation y = 0.000003x^2 – 0.0035x +10.718, with a correlation coefficient R^2 = 1,000, which means it indicates a very high regression coefficient the strong relationship between the acceleration due to gravity and the altitude.

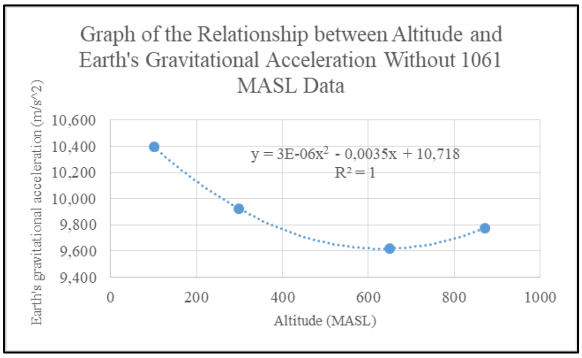

Figure 11. Graph of the relationship between altitude and acceleration due to gravity without 1061 MASL data

Analysis of the first and second data shows different results. Figure 11 fits all the data correctly, while the fifth data of Figure 13 (1061 MASL) deviates far from the fitting curve. In addition, the correlation of the data in the second analysis (Figure 11) shows a maximum regression rate of 1, while the first analysis (Figure 10) shows a lower regression rate of 0,863.

Referring to the second data analysis, by excluding the fifth data (1061 MASL), a perfect fitting curve is obtained with R^2 = 1,000. This means that the fifth data exclusion from the analysis is acceptable. The fifth data deviation (1061 MASL) is caused by the strong and uncontrolled wind direction, which contributes to the acceleration of the observed iron ball fall. The contribution of the wind force to the speed of the falling iron ball increases the momentum (Equation 7), which in turn gives an added value to the Earth's gravitational force (Equation 8) and causes the measured time to be small so that the acceleration value is higher than it should be.

$$\Delta p = m.dv = m.\frac{dx}{dt} \quad (7)$$

$$\Delta F = \frac{dp}{dt} = m.\frac{dv}{dt} \quad (8)$$

In addition, the fifth data deviation is also caused by the characteristics of the smartphone's acoustic sensor, which has a slow response when in an open room compared to a closed room due to the influence of surrounding environmental noise so that the measured time will experience a shift.

Based on the results and discussion, this study provides information related to the acceleration of gravity detection system with variations in altitude reaching the 100-1061 MASL range using the Phypox integrated smartphone acoustic sensor. Measurement of the gravitational acceleration using the smartphone's acoustic sensor provides practicality for researchers to investigate the effect of gravity's acceleration on a place's altitude. This is supported by research by Schwarz et al., (2013) and Abellán-García et al., (2012), that the use of a smartphone as a measuring tool for gravitational acceleration makes it easy for researchers to obtain accurate g measurement data of around (9.796 ± 0.003) m/s^2. In addition, based on research by Kittiravechote & Sujarittham, (2021), the results of the value of the acceleration of gravity carried out by beginners and experts using the Phypox integrated smartphone acoustic sensor show the theoretical value reported by the National Institute of Metrology (Thailand). However, this study has some limitations, resulting in a margin of error for measuring the time on the smartphone acoustic sensor used. The natural acoustic sensor uses sound to provide a stimulus response to the stopwatch, where sound has the speed to reach the smartphone microphone, so there is a correction for the time value described in Table 2. In addition, measuring the fall time still has a factor of sound interference from somewhere measurement, so the acoustic sensor is inconsistent in measuring the time the iron ball falls. The air friction factor on the iron ball also contributes to time correction. This is because when collecting data, researchers still cannot stop the air friction factor, so in the future, a system for measuring the acceleration of gravity is needed which is not affected by air friction.

CONCLUSION

Based on the data analysis above, it can be concluded that the value of the Earth's gravitational acceleration decreases quadratically concerning the altitude of the observation location following the equation $y = 0.000003x^2 - 0.0035x + 10.718$, with y being the value of the Earth's gravitational acceleration and x being the height above sea level. This conclusion is supported by the maximum correlation value with R2 = 1,000

RECOMMENDATION

Based on the limitations of this research, it is hoped that in future research, it will be even better to replace the smartphone's acoustic sensor with a sensor or lighter that is more accurate in measuring time. This is because the acoustic sensor detects sound, which takes time for the sound to reach the microphone on the smartphone. In collecting data for measuring the acceleration of gravity, researchers must pay attention to wind friction and strive to ensure no air resistance to the dropped iron ball. In addition, in using the smartphone acoustic sensor acceleration gravitational measurement system, in the future, the researchers will measure the fall time in a place far from sound disturbances so that the sensor can consistently read the time measurement results. With these suggestions, the acceleration of gravity can be measured more accurately with a smaller margin of error.

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AUTHOR CONTRIBUTIONS

RS contributed to formulating ideas, conducting research designs, designing experimental equipment, and conducting experiments. S contributed to directing the writing of articles, supervising the contents of the articles critically, and providing input regarding ideas. PHW contributed to conducting data analysis and developing discussions. HS contributed by providing input on the design of the experimental equipment and setting up the experiment. NAPH contributed to drafting the article and writing it into the template.

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