What is the Radius of the Earth’s Core?

New Mexico

Supercomputing Challenge

Final Report

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Team 32

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Table of Contents

List of Figures

List of Tables

Executive Summary

The Earth's magnetic field protects the planet from the Sun's harmful solar radiation wind and is created by the rotation of the Earth's metallic core. The magnetic field depends on the size and rotational speed of the Earth's core. A computer code using the Python programming language has been developed called "Earth Outer Core Radius" that analyzes the seismic data obtained from the United States Geological Survey to calculate the radius of the Earth's outer core. The computer code "Earth Outer Core Radius" calculated an average radius of the Earth's outer core of 3580 km. The scientific accepted radius of the Earth's outer core is 3485 ± 3 km. The "Earth Outer Core Radius" program over predicts the outer core radius by 2.7% due to the primary assumption that the Earth's mantle is made up of a single soil layer having a uniform composition and density.

1.0 Introduction

The planet Earth has a core made up of a solid inner core surrounded by a molten-liquid outer core. These two cores combined make up the Earth's core and produces the magnetic field. The Earth's magnetic field surrounds the planet to protect every life form from the Sun's strong solar wind, a stream of charged particles.

The inner core of the Earth is a solid iron core. The outer core is a molten-liquid layer surrounding the solid inner core. It is composed of mostly iron and nickel. It is this molten-liquid core that allows the solid inner core to rotate faster than the rotation of the planet Earth and to produce the magnetic field. The magnetic field depends on the size and rotational speed of the Earth's core. The seismic data from earthquakes is collected by the United States Geological Survey (USGS) and the seismic data is utilized to calculate the radius of the Earth's outer core.

Earthquakes are major geologic events that occur suddenly. They most often occur near the boundaries between tectonic plates (fault zones) because the plates push against each other. When one tectonic plate moves on top of another plate or rubs with another plate, it releases a tremendous amount of energy that produces multiple seismic waves that travel through the Earth. The speed of the seismic waves depends on the composition and density of the soil. By analyzing the detected seismic waves, the Earth's interior composition can be determined. A computer code named "Earth Outer Core Radius" was developed using the Python programming language to analyze the seismic data from the USGS in order to calculate the radius of the Earth's outer core.

1.1 Background

Seismic stations detect and record the earthquakes on seismograms. The USGS collects the seismic (seismograms) data from 486 seismic stations located throughout the United States through its Earthquake Hazards Program [1]. There are two types of seismic waves produced from an earthquake and recorded on seismograms: Body waves and Surface waves.

Most seismic stations only record the body waves because body waves can travel through the interior of the Earth and can be detected far away. Surface waves (i.e., Rayleigh-waves and Love waves) are only recorded by seismic stations located very close to the earthquake because surface waves travel near the surface of the Earth and dissipate rapidly.

Furthermore, there are two types of body waves called Primary-waves (P-waves) and Secondary-waves (S-waves). The seismogram measured by the State Center, IA Seismic Station (US SCIA) for the earthquake that occurred at Lata, Solomon Islands on July 17, 2018 is presented in Figure 1. The seismogram shows the P-wave and the S-wave for the earthquake [2]. The P-waves are compression waves that speed and slow down depending on the composition and density of the soil they are traveling through. The P-waves can travel through the Earth's inner and outer core. Because the P-waves are the first to arrive at the seismic station, they are called Primary-waves (P-waves). The S-waves are shear waves that travel through the mantle of the Earth with more destructive force than the P-waves. The S-waves do not travel through the Earth's core because they get attenuated by the molten-liquid outer core. Because the S-waves arrive later (after the P-waves), they are called Secondary-waves [3].

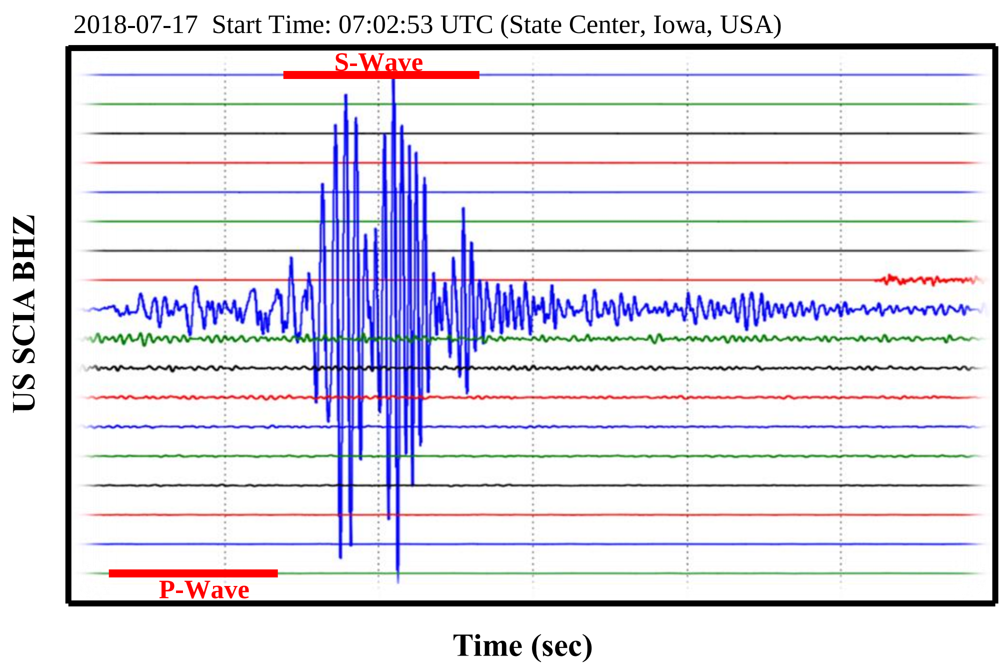

Figure 1. Seismogram for M6-116 km SE of Lata, Solomon Islands Earthquake.

As a result of the S-waves not being able to travel through the Earth's outer core, the outer core shields an area on the opposite side of the earthquake from receiving S-waves and preventing seismic stations from detecting S-waves directly. This shielded area represented is called the S-wave shadowing zone, see Figure 2.

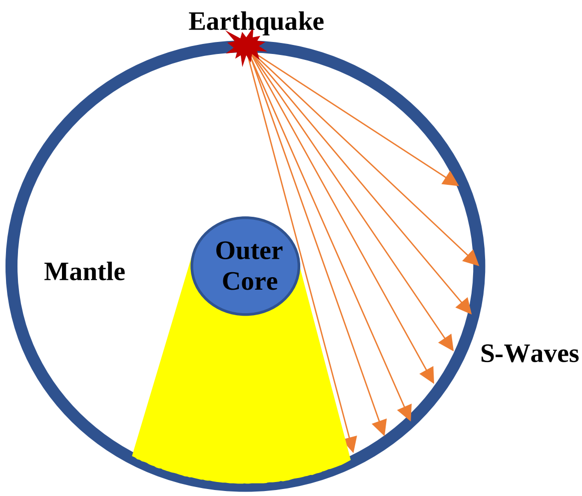

Figure 2. View of the Secondary-Wave Shadowing Zone.

By measuring the angle (as measured from the center of the Earth) or the distance from the earthquake's epicenter and the beginning of the S-wave shadowing zone, the radius of the Earth's outer core can be calculated, see Figure 3. The radius of the Earth's outer core can be calculated by forming an isosceles triangle from three points: Earth's core center, earthquake's epicenter, and the seismic station's location. If the isosceles triangle is cut in half to form a right triangle, the radius of the Earth's outer core is the adjacent side with the obtuse side equal to the Earth's radius and the opposite side equal to half the distance from the earthquake's epicenter to the seismic station's location [4].

The S-waves do not travel in a straight line because the earth is composed of varying concentric soil layers having different compositions and densities. The velocity of the S-waves in the Earth's mantle increases with the depth. Furthermore, the refraction of the S-waves causes the path to follow an upward curvature (bending) direction due to passing through varying soil layers. The velocity and curvature of the S-waves obey Snell's Law [3]. Snell's Law describes the relationship between the velocities and incidence/reflection angles of the S-wave as it travels through a boundary between two different types of soil layers (varying compositions and densities). Snell's Law is utilized to correct the calculated radius of the Earth's outer core due to the curvature (bending) path of the S-wave as it travels from the earthquake's epicenter to the seismic stations.

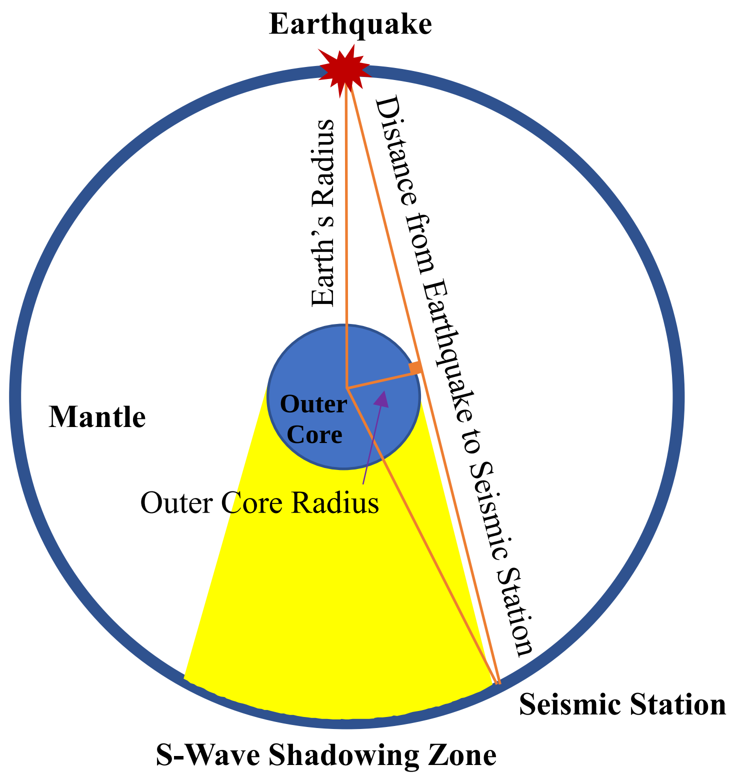

Figure 3. View Showing the Triangle for Calculation of the Outer Core Radius.

1.2 Scientific Accepted Outer Core Radius

The first recording of seismic waves from a remote earthquake occurred in 1889. This scientific breakthrough stimulated the deployment of worldwide observatories and the International Organization of Seismology. The identification of the P-waves and S-waves in seismological records in 1906 allowed the detection of the Earth's core. Because the S-waves do not pass through liquids and the diffraction of the P-waves, the Earth's core was deduced to be made up of two different parts: A solid inner core spinning within an outer liquid core. Seismologists have accurately measured the radius of the Earth's inner and outer core from measuring the seismic waves produced from natural earthquakes and nuclear explosions [5].

Three different scientific methods have been utilized to measure the radius of the Earth's outer core. The first and most accurate scientific method is to determine the distance at which the P-wave is diffracted as it contacts the outer core and use it to calculate the outer core radius. The Earth's outer core shields an area on the opposite side of the earthquake from receiving P-waves and preventing seismic stations from detecting the P-waves directly. This shielded area is called the P-wave shadowing zone and it is similar to the S-wave shadowing zone. Nuclear explosion data, where the location and the origin time are exactly known, were used to calculate the Earth's outer core using this methodology [6, 7]. The second scientific method is to determine the outer core radius from inversion of the normal mode data obtained from analyzing the seismic data. The free oscillation period of the Earth can be calculated from analyzing the seismic data utilized to measure the density of the varying Earth's soil layers. The Earth's outer core has a very high density. The location where the soil density dramatically increases is used to calculate the Earth's outer core radius [8]. The third scientific method is to measure the geomagnetic field from space (satellite geomagnetic data) because the magnetic field produced by magnetization in the Earth's mantle can be distinguished from the field produced by the electric current in the outer core. Based on the detected variation in the magnetic field, the radius of the Earth's outer core can be calculated [9]. The radius of the Earth's outer core has been measured to be 3485 ± 3 km [6].

2.0 Methodology

The Python programming language was utilized to develop a computer code called "Earth Outer Core Radius." The "Earth Outer Core Radius" program analyzes the seismic data collected by the USGS to calculate the radius of the Earth's outer core. The computer code's methodology utilized to analyze the seismic data and to calculate the outer core's radius is:

1. Analyze the seismic data collected by the USGS from all earthquakes that occurred in 2018 from around the world. Only the earthquakes having a Moment Magnitude (M_w) of 6 M_w or greater and occurring within 50 km from the Earth's surface (epicenter) are utilized.
2. Determine which earthquakes are measured by seismic stations located within the United States that showed an S-wave shadowing zone (no S-wave is found on the seismograms). The seismogram data from various seismic stations that are progressively more distant from the earthquake are reviewed to find two seismic stations located close to each other (within 500 km) where by one seismic station detected the S-wave and the other seismic station did not. The angle/distance for the S-wave shadowing zone is measured from the earthquake's epicenter to where the S-wave is no longer detected.
3. Calculate the initial radius of the Earth's outer core using the angle and distance information obtained from calculating the S-wave shadowing zone.

4. Correct the initial calculated outer core radius for the curvature (bending) of the S-wave through the Earth's mantle due to refraction by using Snell's Law and assuming that the density of the mantle is uniform (1-layer soil approximation).
5. Print the calculated average radius of the Earth's outer core, average angle from the earthquake's epicenter to the start of the S-wave shadowing zone, and the average distance from the earthquake's epicenter to the start of the S-wave shadowing zone.

The computer code, "Earth Outer Core Radius," was developed using Canopy Python version 2.7 programming language supported by Enthought, Inc [10].

2.1 Seismic Data Analysis

The USGS seismic data was obtained from the Incorporated Research Institutions for Seismology (IRIS). The USGS collects the seismic data from 486 independent and government funded seismic stations throughout the United States through its Earthquake Hazards Program and gives the seismic data to IRIS which makes the data available to the public via the Data Management System (DMS) [11]. The Earthquake Hazards Program monitors earthquake activity worldwide [1]. The DMS is funded by the National Science Foundation under Cooperative Agreement EAR-1261681 through the "Seismological Facilities for the Advancement of Geoscience and Earth Scope" project [12].

The seismic data received from DMS was preprocessed because only the first line of the seismic data collected by each seismic station for each earthquake was utilized by the computer code. The data was collected into a text file which is read by the computer code and consisted of:

> *Seismic Station Name, Geophysical Coordinate Location, Earthquake Name, Date of Earthquake, Time of the Earthquake, Magnitude, Depth, Geophysical Coordinate Location, Angle from Epicenter to Seismic Station, Distance from Epicenter to Seismic Station, S-Wave Recording.*

The preprocessing of the seismic data was performed to reduce the amount of seismic data that was used by the computer code.

2.2 Seismic Data Criteria

To minimize errors from not knowing the exact location of the earthquake and the start of the S-wave shadowing zone, three criteria are imposed on the seismic data. The computer code checks for these three criteria in the seismic data and will only utilize the data to calculate the radius of the Earth's outer core if the data meets all three criteria. The three criteria are:

1. The earthquake must have a Moment Magnitude of 6 M_w or greater to make it easier to identify the S-wave on the seismogram.
2. The earthquake must be a "shallow" earthquake to eliminate the effects of the earth's varying soil composition and density and the assumption that the earthquake occurs on the surface of the Earth. A shallow earthquake is an earthquake that occurred within 50 km from the Earth's surface (epicenter). This requirement also maximizes the angle and distance from the earthquake's epicenter to the start of the S-wave shadowing zone.
3. The two seismic stations (one measured the S-wave and the other did not) must be located within 500 km of each other to minimize the error in calculating the start of the S-wave shadowing zone.

There were 134 earthquakes around the world in 2018 that had a Moment Magnitude of 6 M_w or greater [1]. Only 10 of the earthquakes met the three criteria stated above. The 10 earthquakes are listed in Table 1.

Table 1. Earthquake Event Information.

Earthquake	Date	Time (UTC)	Magnitude (M_w)	Depth (km)	Location	
					Latitude	Longitude
South of the Fiji Islands	4/2/2018	5:57:35	6.1	42	-24.719	-176.886
Southeast of Lata, Solomon Islands	7/17/2018	7:02:53	6.0	38	-11.594	166.432
West of Kandrian, Papua New Guinea	7/19/2018	18:30:32	6.0	30	-6.114	148.730
Central Mid-Atlantic Ridge	7/23/2018	10:35:59	6.0	10	-0.299	-19.252
West-Northwest of Ile Hunter, New Caledonia	9/10/2018	19:31:37	6.3	12	-21.988	170.158
Drake Passage	10/29/2018	6:54:21	6.3	10	-57.434	-66.383
South-Southeast of Pangai, Tonga	11/10/2018	8:33:21	6.1	35	-20.454	-174.008
East of Visokoi Island South Georgia and South Sandwich Islands	11/15/2018	20:02:22	6.4	15	-56.706	-25.546
Southeast of Pacific Rise	11/15/2018	23:09:01	6.3	10	-56.236	-122.044
Southeast of Easter Island	12/19/2018	1:37:40	6.2	10	-36.118	-101.019

The seismic station information that recorded each earthquake listed in Table 1 and used to calculate the S-wave shadowing zone is presented in Appendix A, *"Seismic Station Event Information."*

2.3 Distance Between Two Points Approximation

The distance between two seismic stations is calculated using the equation for a spherical earth projected to a plane [13]. As a result, the shortest distance between two geographical locations in a flat Earth approximation is a straight line and it is based on the Pythagorean theorem. The equation utilized in the computer code is:

$$D = R\sqrt{(\Delta\alpha)^2 + (\cos(\alpha_m)\Delta\beta)^2}$$

where

D = Distance between two geographical coordinates (Latitude, Longitude) in kilometers

R = Radius of the Earth (6378 km)

$\Delta\alpha$ = Difference in Latitude points ($\alpha_2 - \alpha_1$) in radians

α_m = Mean Latitude [$(\alpha_1 + \alpha_2)/2$] in radians

$\Delta\beta$ = Difference in Longitude points ($\beta_2 - \beta_1$) in radians

For short distances (less than 500 km) and geographical coordinates not located close to the poles, the spherical earth projected to a plane equation gives very good accuracy.

2.4 Earth Mantle Approximation

The S-waves do not travel in a straight line from the location of the earthquake to the seismic stations because the earth is composed of varying concentric soil layers having different compositions and densities. As the S-wave travels from one soil layer to another denser soil layer in the mantle of the Earth, the velocity increases and the direction of the wave curves upward (bending). Figure 4 shows the actual curvature of the S-wave as it travels from the epicenter of the earthquake to the seismic station. The velocity and the curvature direction of the S-wave through the mantle obeys Snell's Law [3]. Snell's Law describes the relationship between the velocities and incidence/reflection angles of the S-wave as it travels through a boundary between two different types of soil layers (varying compositions and densities). Each boundary layer can be represented by a set of multi-variable equations based on Snell's Law. These multi-variable equations can be solved simultaneously as a solution to the multi-variable array. This advance mathematics (e.g., linear algebra) is beyond the scope of this research project.

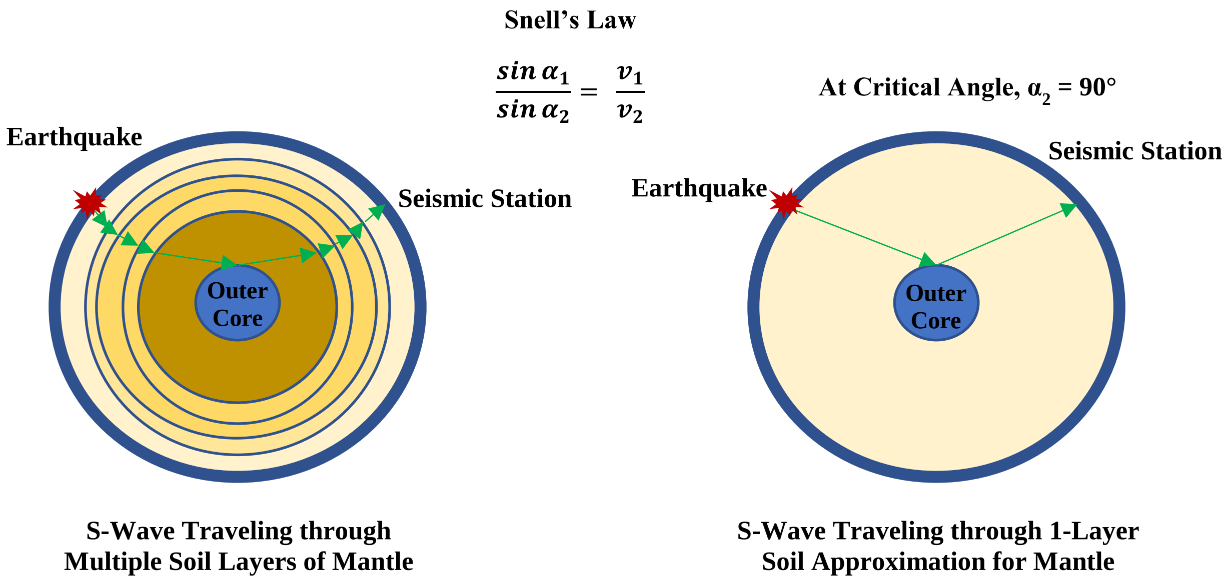

Figure 4. Correction for Refraction of the Secondary-Wave.

A simplification of the Earth's various soil boundary layers is utilized in the calculation. The Earth is assumed to be made up of a single soil layer composition having a constant density. Snell's Law is applied to this simplification to obtain a single equation that approximates the velocity and direction that the S-wave travels from the earthquake to the seismic station locations as it bounces off the outer core layer, see Figure 4.

$$\frac{\sin\alpha_1}{\sin\alpha_2} = \frac{v_1}{v_2}$$

The incidence of the S-wave onto the Earth's outer core causes the S-wave to travel perpendicular to the outer core surface before it reflects back toward the surface of the Earth. Therefore, at the critical angle (α_1) where the S-wave contacts the Earth's outer core, α_1 = 90° and sin 90° = 1. Furthermore, the S-wave is traveling at a velocity (v_1) of 7.49 km/s when it makes contact with the Earth's outer core [5]. As the S-wave travels on the outer core surface, it does not significantly gain speed. Therefore, v_2 is approximately 7.50 km/s. The refraction angle (α_2) can be obtained from Snell's Law. The computer code calculated the refraction angle (α_2) to be 87.04°.

The refraction angle (α_2) is utilized to calculate the curvature of the S-wave as it travels from the earthquake's epicenter to the seismic station location. The calculated curvature distance (e.g., the difference in distance between the maximum curvature of two points and the straight line of two points) is subtracted from the initial calculated radius of the Earth's outer core to obtain the final radius.

2.5 Verification and Validation Analysis

The results of the computer code were independently verified by developing an Excel spreadsheet. The same methodology used in the computer code was utilized in the Excel spreadsheet for only the 10 earthquakes presented in Table 1. The results from the computer code were the same as the results from the Excel spreadsheet. The calculated radius of the Earth's outer core was compared to the scientific accepted outer core radius. The computer code over predicted the outer core radius by 95 km (i.e., 2.7% from the scientific accepted outer core radius).

The location of the seismic stations meeting the third criteria *"two seismic stations must be located within 500 km of each other…"* was validated by using the Global Earthquake Explorer (GEE) program. The GEE program provides an interactive map-based program for viewing earthquakes and the seismograms recorded by seismic stations from around the world. The GEE program was developed by the Department of Geological Sciences of the University of South Carolina [2]. The earthquake data from the GEE program was also used to validate the earthquake data (i.e., location, magnitude, depth) from the DMS because the GEE program uses seismic data from seismic stations located in foreign countries and from the USGS. The earthquake data obtain by foreign seismic stations and used in the GEE program was the same as the earthquake data obtained from the DMS.

3.0 Results

The calculated radius of the Earth's outer core using the seismic data from the earthquakes meeting the above criteria is 3580 km, see Figure 5. The "Calculated Average Radius" line on the graph begins with the first earthquake in 2018 that meet the above criteria. The average calculated angle and distance for the S-wave shadowing zone from shallow earthquakes are 105.0 degrees and 11677 km. The scientific accepted radius of the Earth's core is 3485 ± 3 km [6]. The reported angle and distance for the S-wave shadowing zone for shallow earthquakes are approximately 105 degrees and 11680 km [5]. The computer code calculated outer core radius is off by 95 km (2.7%) due to the following assumptions utilized in the methodology:

a. The earthquake's epicenter is assumed to occur on the surface of the Earth.
b. The average distance between the two seismic stations (one measuring the S-wave and the other not) is assumed to be the beginning of the S-wave shadowing zone and this average distance is used to calculate the angle and distance from the earthquake to the S-wave shadowing zone.
c. The planet Earth's radius is assumed to be constant (6378 km).
d. The density of the Earth's mantle is assumed to have a uniform soil density (1-layer soil approximation).

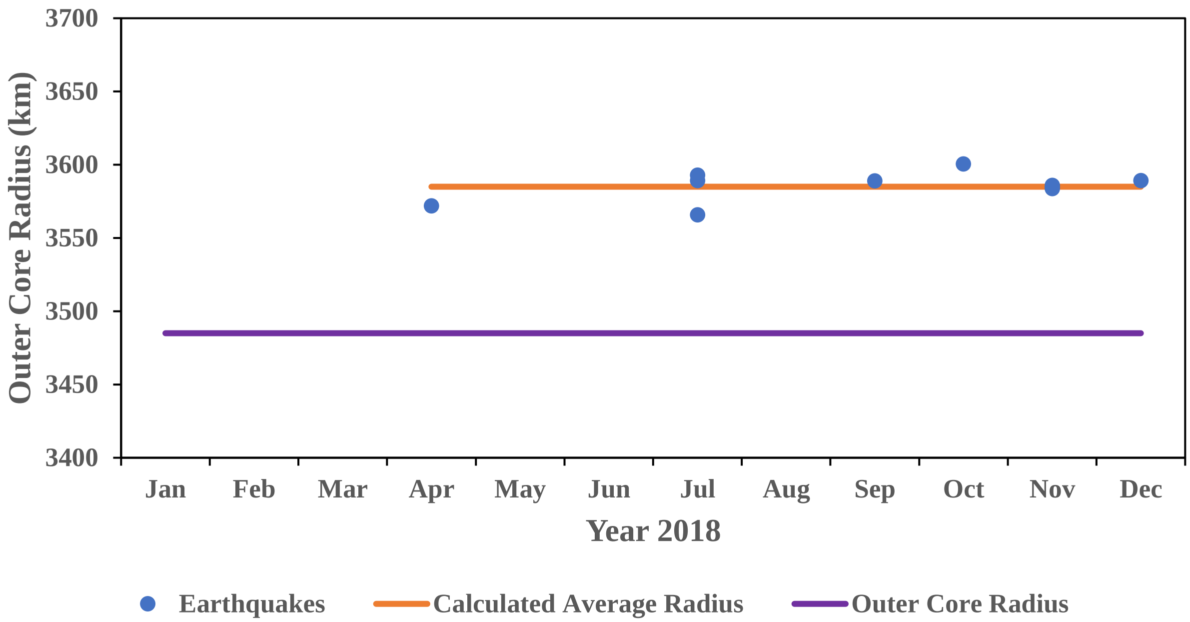

Figure 5. Calculated Average Radius for the Earth's Outer Core.

3.1 Future Development

There are many improvements that can be made to the "Earth Outer Core Radius" program. The short-term improvements are incorporating the varying soil layers of the Earth's mantle to reduce the calculational error. The mantle can be modeled as three distinct boundary soil layers (i.e., Crust, Upper Mantle, and Lower Mantle). This improvement will involve developing a set of multi-variable equations based on Snell's Law to represent the various soil boundary layers in the mantle and simultaneously solving them. The computer code can also be improved by eliminating the assumption that all of the earthquakes occur on the surface of Earth (epicenter). This improvement will involve using spherical trigonometry to correct for the depth of the earthquake at the epicenter location.

By eliminating these two assumptions, the computer code will more accurately calculate the radius of the Earth's outer core within 1% of its true value. Compared to the current scientific methodologies utilized to calculate the outer core radius, this simple methodology calculates the radius of the Earth's outer core very precisely.

The long-term improvement is to have the computer code calculate the P-wave shadowing zone to be able to calculate the radius of the Earth's inner core. The P-waves are refracted by the molten-liquid outer core and are not detected between 104 and 140 degrees from the earthquake's epicenter. By knowing the radius of the inner and outer cores, the volume of molten-liquid can be calculated to better predict the magnitude of the Earth's magnetic field.

4.0 Conclusion

A computer code named "Earth Outer Core Radius" was developed using the Python programming language to analyze the seismic data collected by the USGS in order to calculate the radius of the Earth's outer core. The computer code over predicts the radius of the Earth's outer core by 95 km because the computer code uses a simple 1-layer soil (uniform density) approximation for the Earth's mantle. The Earth's mantle is actually made up of multiple concentric soil layers of varying composition and density that refract/reflect and increase/decrease the velocity of the seismic waves as they pass through the boundary of the varying concentric soil layers owing to Snell's Law. Nevertheless, the difference in the calculated radius to the scientific accepted radius of the Earth's outer core is less than 2.7%.

The methodology of using the S-wave shadowing zone to calculate the radius of the Earth's outer core is simple to use and gives an acceptable result compared to the other scientific methods utilized to calculate the outer core radius. The size of the outer core is important because the molten-liquid iron/nickel layer surrounding the solid inner core allows the inner core to move independently of the planet Earth's rotation which produces an electric current in the molten-liquid outer core due to circulation and convection and thus, generates the Earth's magnetic field. This simpler methodology can be used to model the effects of the size of the Earth's core within programs developed to model the Earth's magnetic field. One such program widely used by seismologists is the Preliminary Reference Earth Model (PREM) developed by the International Association of Geodesy [14]. Incorporating this simpler methodology into PREM will simplify the model without sacrificing accuracy.

5.0 Significant Achievement

This research project offers a simple solution to a complicated science problem. It shows that anyone with a curious mind and determination can perform scientific research and solve complicated science problems.

This research project was very difficult to perform because of the initial lack of mathematical and physics knowledge. I had to learn Python programming language, algebra, trigonometry, physics, and geology to perform this project. My significant achievement was completing this difficult research project. I am very proud of myself for this major accomplishment. I learned that I can accomplish anything if I set my mind to doing it.

6.0 Acknowledgement

I would like to acknowledge Curtis B. Terrill (my sponsoring teacher), Mark B. Petersen (my Python computer programming mentor), and Ruben Rangel (my geologist mentor). Terrill is a Science Teacher at Los Alamos Middle School, Petersen is a Climate Scientist at Los Alamos National Laboratory, and Rangel is a Geology Consultant for the United States Department of Energy - Los Alamos Field Office. I would also like to thank my parents, Santiago and Norma Parra, for encouraging me to complete this project and not letting me quit.

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8.0 Appendix

Appendix A. Seismic Station Event Information.

Table A. Seismic Stations Meeting the Data Criteria.

Earthquake Event	Date	Time (UTC)	Magnitude (Mw)	Depth (km)	Location		Seismic Station	Angle (Deg)	Distance (km)	Location		S-Wave Recording
					Latitude	Longitude				Latitude	Longitude	
M6.1-S of the Fiji Islands	4/2/2018	05:57:35	6.1	42	-24.719	-176.8865	Northview High School, Brazil, IN	105.23	11700.37	39.52	-87.17	Y
							Eastern Greene Jr/Sr High School, Bloomington, IN	105.38	11717.46	39.04	-86.74	N
M6.0-116km SE of Lata, Solomon Islands	7/17/2018	07:02:53	6.0	38	-11.5936	166.432	State Center, IA	105.38	11717.38	41.91	-93.22	Y
							MacAlester College, St. Paul, MN	105.49	11729.77	44.94	-93.17	N
M6.0-91km W of Kandrian, Papua New Guinea	7/19/2018	18:30:32	6.0	30	-6.1139	148.7302	LASA Array, MT	104.75	11646.91	46.69	-106.22	Y
							Casper, WY	104.97	11671.54	42.65	-106.52	N
M6.0-Central Mid-Atlantic Ridge	7/23/2018	10:35:59	6.0	10	-0.2994	-19.252	Anaktuvuk Pass, AK	104.88	11661.31	68.13	-151.81	Y
							Knifeblade Ridge, AK	105.00	11674.84	69.16	-154.78	N
M6.3-200km W-NW of Ile Hunter, New Caledonia	9/10/2018	19:31:37	6.3	12	-21.988	170.1584	Hockley, TX	104.07	11571.44	29.96	-95.84	Y
							Oklahoma Geological Survey Observatory, Leonard, OK	105.82	11766.23	35.91	-95.74	N
M6.3-Drake Passage	10/29/2018	06:54:21	6.3	10	-57.434	-66.3834	Troy Canyon, Currant, NV	104.30	11579.61	38.35	-115.59	Y
							Dugway, Tooele County, UT	105.10	11686.23	40.19	-112.81	N
M6.1-80km SSE of Pangai, Tonga	11/10/2018	08:33:21	6.1	35	-20.4538	-174.0081	Blacksburg, VA	104.95	11669.72	37.21	-80.42	Y
							Nordonia Hills Middle School, Northfield, OH	105.13	11689.69	41.32	-81.54	N
M6.4-101km E of Visokoi Island South Georgia and South Sandwich Islands	11/15/2018	20:02:22	6.4	15	-56.7065	-25.546	Blacksbury, VA	104.71	11642.94	37.21	-80.42	Y
							Tazewall, TN	105.31	11709.34	36.54	-83.55	N
M6.3-SE of Pacific Rise	11/15/2018	23:09:01	6.3	10	-56.2363	-122.0441	Erie, PA	104.56	11626.33	42.12	-79.99	Y
							Minisink Valley Middle School, Slate Hill, NY	105.55	11735.57	41.38	-74.52	N
M6.2-SE of Easter Island	12/19/2018	01:37:40	6.2	10	-36.118	-101.019	Contact Creek, Katmai, AK	104.88	11661.60	58.26	-155.89	Y
							Pilot Point, AK	105.00	11674.46	57.57	-157.57	N