DETERMINING THE DIRECTION OF COSMIC RAYS

(Richard Buck, Louisville High School, Woodland Hills, CA)

BACKGROUND

This module contains three exercises to help the student understand some basic principles involved in calculating the direction from which cosmic rays arrive when they strike the earth. Cosmic rays are extremely high-energy subatomic particles that create showers of other subatomic particles when they hit the atmosphere and interact with the molecules and atoms there. The shower has the shape of a curved wave front whose curvature, size and particle density depends on the energy of the cosmic ray particle creating the front. Cosmic ray detectors can determine the direction of an approaching wave front within a 45-degree angle from vertical.

APPROACH

In these exercises the wave front will be simplified to appear as planar wave (a straight line without any particular thickness). This will allow the basic concepts to be grasped and a comparatively simple math approach to be used.

OBJECTIVES

- To enable students to create a visual model of the wave front generated in a cosmic ray shower.
- To enable students to create a model of how a cosmic ray detector determines cosmic ray direction.
- To enable students to use trigonometry and kinematics equations to calculate the direction from which a cosmic ray has approached the Earth.

CALIFORNIA STATE STANDARDS ADDRESSED

Science Standards

Motion and Forces

1a) Students know how to solve problems that involve constant speed and average speed.

Investigation and Experimentation –

1a) Select and use appropriate tools and technology (such as computer-linked probes, spreadsheets and graphing calculators) to perform tests, collect data, analyze relationships and display data.
1b) Identify and communicate sources of unavoidable experimental error.
1d) Formulate explanations by using logic and evidence.
1g) Students recognize the usefulness and limitations of models and theories as scientific representations of reality.

Math Standards

Trigonometry

(1.0) Students understand notion of angle and how to measure in both degrees and radians…

(2.0) Students know the definition of sine and cosine as Y- and X- coordinates of points on the unit circle…

(19.0) Students are adept at using trigonometry in a variety of applications and word problems.

Geometry

(8.0) Students know, derive and solve problems involving the perimeter, circumference, area, volume, lateral area and surface area of common geometric figures.

(12.0) Students find and use measures of sides and of interior and exterior angles of triangles and polygons to classify figures and solve problems.

(22.0) Students know the effect of rigid motions on figures in the coordinate plane and space, including rotations, translations, and reflections.

RESOURCE

1) http://csr.phys.ualberta.ca/~alta/Pages/Technical_Publications/Papers_Resources_References/p491v4.html

EXERCISES

A) The first exercise is a tactile demonstration that allows the student to get a feeling for how two cosmic ray detector sites can be used to determine wave front angle by noting different response time intervals. ***ESTIMATED TIME = 20 MIN.***

B) The second exercise uses a moving object to represent the wave front (a rolling pipe) and two objects (beads) that represent two detector sites at differing angles to the approaching wave front. The angle of approach will be calculated knowing the speed of the wave, separation of the beads and time interval between the strike of the first bead and the second. ***ESTIMATED TIME = 45 MIN.***

C) The third exercise involves calculating realistic time intervals recorded by the two detector sites using realistic wave front speeds (close to the speed of light). ***ESTIMATED TIME = 20 MIN.***

D) The fourth exercise allows students to expand on the activities above and create a three-dimensional model of a cosmic ray wave front. ***ESTIMATED TIME = 45 MIN.***

PIN THE TAIL ON THE COSMIC RAY

OBJECTIVE

The purpose of this exercise is to allow the student to get a feeling for how two cosmic ray detector sites can be used to determine a wave front angle by noting different time intervals of response.

MATERIALS – for groups of 3 students

Each group of three students needs the following:
2 pieces of wire about 20 cm long (pieces of cut-up coat hanger works well)
1 piece of string about 1 meter long
1 blindfold (optional)

PROCEDURE (ESTIMATED TIME = 20 MIN.)

A) Each student in a group of three should take turns holding the two wires. The wires are held in separate hands at arm length, shoulder width, directly in front of the student. The wires should be held relatively loosely so that they hang straight down. The student should either be blindfolded or keep their eyes closed.
B) The other two students will take the string and holding it stretched out between them, move the string at a **constant speed** toward the two wires.
C) The blindfolded student will make mental notes of which wire is struck first and the time interval between the strike of the first wire and strike of the second wire.
D) The two students with the string will then vary the direction of approach to the wires, randomly coming from directly in front of the blindfolded student so that the wires are struck simultaneously or at different angles of approach from the right and the left. The students should make every effort to maintain the **same speed** of approach no matter what direction they are approaching.

QUESTIONS

1. Being blindfolded how could you tell when the string is approaching from directly in front of you (parallel to the plane of the wire detectors)?

2. How can you tell when the string approaches from the right or the left?

3. How can you differentiate between approaches from small or large angles, relative to a straight-on direction (as in question #1, 0 degrees)?

4. What is the direction of approach that gives the largest time interval of strike?

5. Why would the answers to the above questions be difficult to determine if the speed of the string or the distance between the wire detectors varied during the experiment?

VARIABLES AFFECTING COSMIC RAY DETECTION

OBJECTIVE

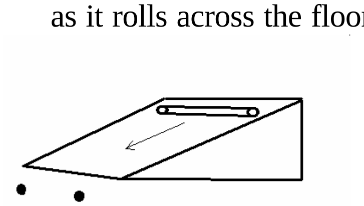
To calculate the approaching angle of a wave front knowing the speed of the wave, separation of the detector sites and time interval between the strike of the first detector site and the second.

MATERIALS – for groups of 3 students

Each group of three students should have the following:
1 length of plumbing pipe (about 40 cm long and 1 cm in diameter) or a solid metal rod
1 piece of board (about 50 cm x 50 cm x 0.3 cm) or as thin as possible without flexing.
2 small plastic beads with holes through them or flat sides so they sit still
1 piece of white construction paper (about 50 cm x 50 cm)
1 meter stick
1 to 3 stopwatches

PROCEDURE (ESTIMATED TIME = 45 MIN.)

A) Set the board at a small angle of tilt by propping up one end (just enough to allow the pipe to roll down without much acceleration). You want the pipe to be able to roll across the floor when it leaves the board at a speed that is not so fast that time measurements are difficult to make, yet not so slow that it tends to lose much speed as it rolls across the floor.

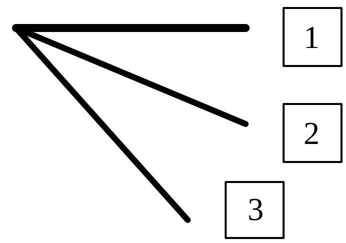


B) Set the pipe at the top of the board (parallel to the top edge) and hold it with one finger at its center. Release the pipe so that it rolls down the board and strikes the floor evenly (one end does not hit noticeably before the other).

C) Place a meter stick at the base of the incline so that you may determine the average speed of the pipe as it rolls ***across the floor*** (using V = D/T). Repeat the distance and time measurements twice more or if you have 3 stopwatches use the 3 times. Average out the 3 measurements then calculate and record the average speed below.
Distance = _________ Average Time = ___________
Average Speed when released from top = ___________

D) Draw a line on the board parallel to and 20 cm below the top. Start the pipe from the line and calculate the average speed as before from this point. It should be significantly less than the speed in Part “C”. Why?
Distance = _________ Average Time = ___________
Average Speed when released from 20 cm line = ___________

E) Place the white construction paper at the base of the board. Draw 3 lines on the paper all starting from the same point. The first line should be about 20 cm long and parallel to the base of the board. The second should start from the same point as the parallel line and at an angle of 30^o below it. The third line should also start from the same point and at an angle of 45^o below the first. USE A PROTRACTOR. (The diagram is not to scale.)



F) The lines will be used to position the beads. The beads will then represent positions of the two cosmic ray detector sites at 3 angles to the wave front. Position the two beads (20 cm apart) on the line parallel to the base. Roll the pipe from the top of the board; the pipe should hit the beads simultaneously. What is the time interval for this simultaneous event (this should be obvious)?
Average Time Interval for LINE 1 strikes = _______________

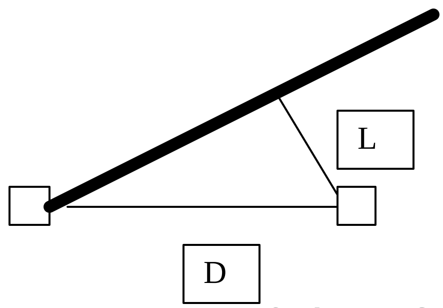
G) Position the two beads (20 cm apart) on the line 30^o below the line parallel to the base. Roll the pipe from the top of the board. Note the time interval between bead strikes (start the watch when the pipe hits the first bead and stop it when it hits the second). Repeat the measurement 3 times and record the average time below.
Average Time Interval for LINE 2 strikes = _______________

H) Position the two beads (20 cm apart) on the line 45^o below the line parallel to the base. Roll the pipe from the top of the board. Note the time interval between bead strikes (start the watch when the pipe hits the first bead and stop it when it hits the second). Repeat the measurement 3 times and record the average time below.
Average Time Interval for LINE 3 strikes = _______________

I) Calculate the angles of the wave front to the bead detector sites according to the equation:

$$\textbf{ANGLE} = \textbf{SIN}^{-1}\ (\textbf{V*T / D})$$

This equation is derived from the diagram below. The diagram represents a wave front (heavy line) striking one detector site (box on left). The distance of the wave front to the second detector site (narrow line labeled "L") is determined by L = VT (V = velocity of the wave front, T = time interval between detector strikes). Note that the wave front, the narrow line "L" and the distance between the detectors "D" forms a right triangle and the angle computed is the angle of the wave front to the ground (horizontal). Since the direction of the wave front is perpendicular to the wave front the angle calculated will be the angle of approach from the vertical.



PIPE STARTING AT TOP OF BOARD

LINE	WAVE VELOCITY (M/S)	TIME (S)	BEAD DISTANCE (D)	ANGLE (DEG)
1				
2				
3				

J) Compare the angles calculated with the angles you have drawn on the construction paper (measured). Determine the % Difference according to the equation:
% Difference = (Calculated Value - Measured Value) / (Measured Value) x 100%

LINE	MEASURED VALUE	CALCULATED VALUE	% DIFFERENCE
1			
2			
3			

K) Repeat the experiment for a different wave front speed (starting the pipe at the line 20 cm below the top of the board).

PIPE STARTING AT 20 cm LINE

LINE	WAVE VELOCITY (M/S)	TIME (S)	BEAD DISTANCE (M)	ANGLE (DEG)
1				
2				
3				

L) Compare the angles calculated with the angles you have drawn on the construction paper (measured). Calculate the % Difference according to the equation:
% Difference = (Calculated Value - Measured Value) / (Measured Value) x 100%

LINE	MEASURED VALUE	CALCULATED VALUE	% DIFFERENCE
1			
2			
3			

M) Repeat the experiment for a different detector spread (move the beads 10 cm apart) and the pipe starting at the top of the board.

CLOSE BEAD SPREAD

LINE	WAVE VELOCITY (M/S)	TIME (S)	BEAD DISTANCE (M)	ANGLE (DEG)
1				
2				
3				

N) Compare the angles calculated with the angles you have drawn on the construction paper (measured). Calculate the % Difference according to the equation:
% Difference = (Calculated Value - Measured Value) / (Measured Value) x 100%

LINE	MEASURED VALUE	CALCULATED VALUE	% DIFFERENCE
1			
2			
3			

GRAPHS

Using either graph paper, a graphing calculator, or a spreadsheet program create a graph of Measured Angle (Y axis) vs. Time Interval (X axis). On this graph you will have 3 lines: Pipe Starting at Top, Pipe Starting at 20 cm Line, and Close Bead Spread. Using this graph and the data from the tables above answer the following questions.

QUESTIONS

1) How well does this experiment predict the direction of the wave front to the bead detector sites? On what do you base your answer?

2) What kind of errors might have occurred that diminished the ability of this experiment to predict the direction of the wave front? Be specific.

3) What effect does increasing the **angle** of the incoming wave front have on the time interval recorded by the detector sites? What evidence do you have for your answer?

4) What effect does increasing the **speed** of the incoming wave front have on the time interval recorded by the detector sites? What evidence do you have for your answer?

5) What effect does increasing the **distance** between detectors have on the time interval recorded by the detector sites? What evidence do you have for your answer?

6) What other variables can you think of that might affect the time interval, either in this experiment or in an actual cosmic ray experiment?

CALCULATING REALISTIC TIME INTERVALS

OBJECTIVE

To calculate realistic time intervals recorded by the two detector sites using realistic wave front speeds (close to the speed of light).

MATERIALS – individual students

Pencil, Paper, Calculator

PROCEDURE (ESTIMATED TIME = 20 MIN.)

Perform the following calculations and answer the questions.

1) Since cosmic ray showers travel near the speed of light (about 3.0×10^8 m/s), what would be the time interval recorded between two detector sites if the wave front traveled so that its direction of motion was 30^o to the vertical (wave front at a 30^o angle to the ground)? Assume the two detector sites are 2.0 kilometers apart. Be sure to pay attention to the units given.

2) Using the equation from the previous exercise, **ANGLE = SIN^{-1} (VT / D)**, determine the minimum angle that the detector sites can accurately "see" if they can record down to only a 1 nanosecond time interval (precise to 1×10^{-9} seconds). Assume the two detector sites are 2.0 kilometers apart.

3) What would be the effect of increasing the distance between the two detector sites? Would the angle "seen" be increased, decreased or remain the same? How did you determine your answer?

4) What benefits and problems can you foresee with placing the cosmic ray detectors further and further apart? Consider the angle "seen", the ability to detect showers of different size and any other factors you can think of.

A THREE DIMENSIONAL MODEL - LOCATING COSMIC RAY SOURCE

OBJECTIVE

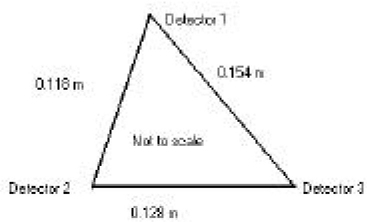
To use data from three hypothetical cosmic ray detector sites to locate the source of a local particle shower.

MATERIALS – for groups of 2 to 3 students

Plastic board with graphing grid or graph paper, Clay lump (about 1 cm^3), 3 Thin Wires (about 10 cm long), Small Protractor, Pencil, paper, calculator

PROCEDURE (ESTIMATED TIME = 45 MIN.)

A) Place 3 small (marble-sized) lumps of clay on the graph with the following spacing; 0.118 m, 0.154 m, 0.128 m. Assign coordinate points to these lumps according to the spacing of the squares on your graph.



The coordinates represent 3 hypothetical cosmic ray detector sites. Their geographic positions (latitude and longitude) are represented by the X and Y values of the coordinates.

B) A cosmic ray particle shower will now strike the detector sites. We will approximate that the shower arrives as wave with a flat (planar) structure and at an angle to the surface of the ground (grid) with a velocity of 1.0000 m/s (obviously way too slow, but this makes the model easier to deal with). The detector sites will record the particle wave strike at times determined by the detector sites' GPS activated clocks (Global Positioning Satellite). For simplicity, assume the time that Detector Site 1 is activated is 0.0000 seconds. The time recorded by the other detector sites are given in the data table below.

Detector Site	Time of Arrival (seconds)
1	0.0000
2	0.0490
3	0.0373

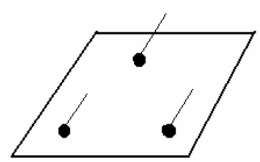
C) Using the above times, the detector site spacing (D), the velocity of the wave (V), and the equation: **ANGLE =** $\mathbf{Sin^{-1}}$ **(V*T/D)**, where T is the Time Interval between detector sites.

i) Calculate the time intervals of the wave arrival for Detector Site 1 to 3, Detector Site 1 to 2, and Detector Site 3 to 2. Enter these values in the data table below.

ii) Next calculate the angles of arrival of the wave front by calculating the angle for Detector Site 1 & 3, then Detector Site 1 & 2 and Detector Site 3 to 2. Enter these values in the data table below.

Detector Site grouping	Time Intervals (seconds)	Angle (degrees)
Detector Site 1 to 2		
Detector Site 1 to 3		
Detector Site 3 to 2		

D) Place the wires into the clay detector sites on the grid at the angles indicated by the above data table. Do this by placing a protractor parallel to a line connecting the detector sites and adjusting the wire angles, from vertical. Do this angle adjusting from all three viewpoints (the 3 sides of the detector triangle). See the diagram below.



E) Measure the angles of the wires from vertical, for two points of view; parallel to the X-axis of the grid and parallel to the Y-axis of the grid. These angles represent the directions of the wires with respect to what they are pointing (positions in the sky). The X-axis can represent a coordinate system in the sky called RIGHT ASCENSION (similar to longitude on Earth), the Y-axis can represent a coordinate system called DECLINATION (similar to longitude on Earth). Enter the data in the table below

Axis	Angle (degrees)
X	
Y	

QUESTIONS

1. Describe the orientation of the three wires. Are they essentially parallel to each other? Should they be?

2. How does the orientation of the wires relate to the cosmic ray particle wave front? Did the wave front move in a direction perpendicular to the ground?

3. Why did the wave front strike the three different detector sites at different times? How could it have struck all three simultaneously?

4. If the detector sites were not on a level grid, in other words at different altitudes from sea level, how would you have to account for this altitude difference in your calculations?

5. Although you calculated three time intervals in this activity why would you need only two time intervals to determine the direction of the wave front as the detector sites are set up here?

6. Since only two of the detector site time intervals (Detector Site 1 to 2 and Detector Site 1 to 3) are needed to determine the position of all three wires, what would the time interval be between Detector Site 3 to 2 if you measured the wire angles to be 5 degrees from vertical along a line parallel to Detector Site 2 and 3? Show your calculations below.