**TEACHER GUIDE**

Physics

**RADAR: Doppler Effect in Action**

**Topic(s):** Radar, Doppler Effect

**Grade level(s):** 9th – 12thgrades

**Time:** 45-60 minutes

**NGSS Alignment**: HS-PS4-5

**TEKS Alignment**: PHYS.7.D

**Virginia Science SOL Alignment**: PH.5C

**ACTIVITY OVERVIEW**

In this activity, students are introduced to the radar and the Doppler effect as well as how it applies to plane detection and air traffic control. Students will use a constructed radar box to model the data collected by radar systems. Students will use the provided equipment to identify the object of a shape they cannot see by using the equipment to measure the distance to the object from a sensor. Students will also collect simulated data of an object in motion to see how the same equipment can relay information of not only distance but movement and direction as well. Students will see how this applies to the Department of Defense and understand the need for updated radar systems to detect fast-moving and low-flying vehicles.

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**ALIGNMENT TO STANDARDS**

**NGSS:**

**HS-PS4-5.** Communicate technical information about how some technological devices use the principles of wave behavior and wave interactions with matter to transmit and capture information and energy.

**TEKS:**

**PHYS.7.D.** Investigate behaviors of waves, including reflection, refraction, diffraction, interference, resonance, and the Doppler effect

**Virginia Science SOL:**

**PH.5C.** Wave interactions are a part of everyday experiences

**LEARNING OUTCOMES**

Students will know:

* What radar is.
* How radar can be applied in different fields/industries.

Students will understand:

* How the Doppler Effect is used in radar to detect motion of objects.
* How radar/sonar/ etc can be used for imaging.
* That our current radar systems will need to be updated to view and track hypersonic vehicles.

Students will be able to:

* Manipulate a radar model to collect data about the distance between an object and a sensor.
* Graph collected data and work as a group to combine their perspectives (X-axis, Y-Axis, and Z-axis) to determine an object’s shape.
* Collect data about an objects motion and work as a group to combine their perspectives (X-axis, Y-axis, and Z-axis) to determine an object’s path of motion.
* Explain how hypersonic vehicles evade current radar setups.

**CAREER CONNECTIONS**

**Electrical and Electronics Engineers**

Electrical engineers design, develop, test, and supervise the manufacture of electrical equipment.

**Work Environment:** Electrical and electronics engineers work in industries including research and development, engineering services, manufacturing, telecommunications, and the federal government. Electrical and electronics engineers generally work indoors in offices. However, they may have to visit sites to observe a problem or a piece of complex equipment.

**Duties:** Electrical engineers design, develop, test, and supervise the manufacture of electrical equipment, such as electric motors, radar and navigation systems, communications systems, or power generation equipment. Electrical engineers also design the electrical systems of automobiles and aircraft. Electronics engineers design and develop electronic equipment, including broadcast and communications systems, such as portable music players and Global Positioning System (GPS) devices. Many also work in areas closely related to computer hardware.

**Median Salary:** $109,010 (US Bureau of Labor, 2023)

Source: <https://www.bls.gov/ooh/architecture-and-engineering/electrical-and-electronics-engineers.htm>

**Air Traffic Controllers**

Air traffic controllers coordinate the movement of aircraft to maintain safe distances between them.

**Work Environment**: Air traffic controllers work in control towers, approach control facilities, or en route centers. Their work can be stressful because maximum concentration is required at all times. Night, weekend, and rotating shifts are common.

**Duties:** Professionals in these jobs have the following duties and more: Monitor and direct the movement of aircraft on the ground and in the air, transfer control of departing flights to other traffic control centers and accept control of arriving flights, and inform pilots about weather, runway closures, and other critical information

**Median US Salary**: $137,380 (US Bureau of Labor, 2023)

Source: <https://www.bls.gov/ooh/transportation-and-material-moving/air-traffic-controllers.htm>

**Aircraft and Avionics Equipment Mechanics and Technicians**

Aircraft and avionics equipment mechanics and technicians repair and perform scheduled maintenance on aircraft.

**Work Environment**: Aircraft and avionics equipment mechanics and technicians work in hangars, in repair stations, or on airfields. The environment can be loud because of aircraft engines and equipment.

**Duties:** Professionals in these jobs have the following duties and more: diagnose mechanical or electrical problems, repair wings, brakes, electrical systems, and other aircraft components, and repair and maintain a plane’s electronic instruments, such as radio communication devices and equipment, radar systems, and navigation aids. As the use of digital technology increases, more time is spent maintaining computer systems.

**Median US Salary**: $75,400 (US Bureau of Labor, 2023)

Source: <https://www.bls.gov/ooh/installation-maintenance-and-repair/aircraft-and-avionics-equipment-mechanics-and-technicians.htm>

**BACKGROUND INFORMATION**

Radar (Radio Detection And Ranging) is an instrument that can detect surrounding objects using radio waves. Thus, in the maritime and aviation world, objects such as ships, buoys, birds, or planes can be detected by radars. The use of short-wavelength microwaves allows a very accurate measurement of the direction in which the object is detected and the distance at which it is located. Radars have many other applications such as meteorology and aerial surveillance. Radars are also widely used in everyday life to measure the speed of cars on a road or the speed of a tennis ball on a court for example.

Although not using sound waves but short-wave microwaves, the principle of a radar is the same as that of sound. When in contact with an object, the waves reflect and thus, the distance to the target and its direction can be accurately calculated. This information is then put in the form of visual data on a screen so it becomes readable.

Let's suppose that a wave is sent to one specific direction. The wave passes through its environment in a straight line, but when it hits an object on its path, it is reflected and part of this wave returns to its original position. This phenomenon is called reflection. It is the time it takes for this echo to return that will help to accurately determine the distance at which the object is located.

Since the microwaves used with radars have an extremely short wavelength, they must be considered as waves going in a straight line like visible light. Microwaves are not refracted by the ionosphere like other waves below 30 MHz, so they can be considered as straight propagating waves over a visible distance.

Unlike visible light, microwaves are not absorbed by clouds or mist and remain generally unattenuated. These waves are therefore considered the ideal wavelength for navigation. The two main frequency bands used for navigation are the 3000MHz S-bands and the 9000MHz X-bands.

Resources

History of Radar

* <https://www.spartan.edu/news/the-history-of-radar/>

Introduction to Radar

* <https://www.arrow.com/en/research-and-events/articles/introduction-to-radar>

Why Hypersonic Missles’ Greatest Strength Also Makes Them Vulnerable

* <https://www.airandspaceforces.com/hypersonic-missiles-tracking-space-sensor/#:~:text=A%20screenshot%20from%20a%20new,technologies%20could%20evade%20current%20sensors>.

Radar Engineers Adapt to Hypersonic Challenges

* <https://www.ni.com/en/perspectives/radar-engineers-adapt-to-hypersonic-challenges.html>

Hypersonic Weapons Demand Longer-Range Radars and Space-Based Sensors for Detection

* <https://militaryembedded.com/radar-ew/sensors/hypersonic-weapons-demand-longer-range-radars-and-space-based-sensors-for-detection>

Waves and Frequency Ranges

* <https://www.radartutorial.eu/07.waves/Waves%20and%20Frequency%20Ranges.en.html>

**PRE-LAB RECOMMENDATIONS**

Before this lesson, we recommend reviewing wave properties and the electromagnetic spectrum with the following resources.

Wave Properties: <https://www.learningundefeated.org/project/whats-in-a-wave-dlb/>

Electromagnetic Spectrum: <https://serpmedia.org/scigen/e5.3.html>

**POST-LAB RECOMMENDATIONS**

After this lesson, we recommend continuing the conversation about hypersonic vehicles and the challenge to detect them. The following activity uses hypersonics as a context to apply optics content.

Reflecting on Hypersonics: [https://static1.squarespace.com/static/638e4ab84460f61414edfba1/t/660ecb581ea1bb27012b1549/1712245592809/Hypersonics+Lesson+Plan+HS+Physics+-+Reflecting+on+Hypersonics.pdf](https://static1.squarespace.com/static/638e4ab84460f61414edfba1/t/660ecb581ea1bb27012b1549/1712245592809/Hypersonics%2BLesson%2BPlan%2BHS%2BPhysics%2B-%2BReflecting%2Bon%2BHypersonics.pdf)

More Hypersonics curriculum from Air & Space STEM Outreach is available here: <https://www.afosrstem.org/hypersonics>

**PREPARATIONS**

RADAR Box Prep

* Place the box at the student table and plug in the 4 power cords
* Ensure the switch is in the off position
* Place the table in the box over the mounted Servo. Place a unique 3-dimensional shape in the center of the table.

**STUDENT STATION SET-UP**

Students will work in pairs at an individual station and will share the radar box with the groups at their table.

1. Radar Box (per table)
	1. Z-axis stations should also be provided a plastic support for their cursor.
2. Pencils

**MATERIALS NEEDED FOR DEMOS**

1. Foam ball
	1. Can be used for initial demo on the island and for the doppler ball
2. 9V battery
3. Buzzer with 9V connection

**LESSON PLAN**

**Introduction (5-10 min)**

* Welcome students to the lab and direct them to take a seat.
* Explain to students that they will be learning about radar.
* Ask students if they have heard of radar before. If not, what does it make them think of?
	+ Options to engage:
		- Have students discuss as a table for 60 seconds then report back.
		- Have students write on scrap paper their ideas, collect after 60 seconds.
		- Think for 10 seconds, Pair for 30 seconds, then share with the class.
	+ Students might know it informally as something that has come to the attention of a person or group. (For example, I have a lot going on, but I know I need to take the dog out, it’s on my radar).
	+ Students might associate it with car speed detection by speed cameras or the police.
	+ Students might associate it with planes and air traffic control.
* Explain that radar is a system for detecting the presence, direction, distance, and speed of aircraft, ships, and other objects. It’s found at all airports, you’ve probably even seen it spinning in circles off the landing strip. It helps air traffic controllers to see where the incoming planes are and coordinate take-off for departing planes.
* So how does radar work? It’s very similar to echolocation that we see in nature. Ask students what they know about echolocation or what it makes them think of.
	+ Options to engage:
		- Have students discuss as a table for 60 seconds then report back
		- Have students write on scrap paper their ideas, collect after 60 seconds
		- Think for 10 seconds, Pair for 30 seconds, then share with the class
	+ Echolocation is the location of objects by reflected sound. It’s common in animals such as dolphins and bats. These animals emit calls and listen to the echoes of those calls that return from various objects near them.
* Ask for a volunteer from the class to help with a demonstration and for the class to stand around the center island to watch.
	+ Have the volunteer stand at one end of the island with a ball. Explain to the class that the volunteer will have their eyes closed and will roll the ball on the table towards a barrier that the instructor will place. The volunteer’s goal is to determine if the barrier was close (within 3 feet) or far (further than 3 feet).
		- The barrier can be a book or folder. Anything to block the ball’s path and bounce it back to the volunteer.
	+ Do this 2-3 times.
	+ Ask the volunteer and the class how they were able to determine if the barrier was close or far.
		- How quickly the ball returned. The further the barrier was the longer it took the ball to travel to the barrier and back to the volunteer.
* Explain that sonar (Sound navigation and ranging) and Radar (radio detection and ranging) use the same principle to detect objects in their path. Sonar uses sound, sometimes ultrasounds (high frequency that we can’t hear), and radar uses radio and microwaves.
* Explain that the core use for these technologies is to see what our eyes cannot. Ultrasounds can help us to image organs under the skin. Radar can help to detect planes over 50 miles away.
* Explain that today we’ll be putting radar to the test to see if it will help us to “View” an object in an opaque box.

**Part 1: From Distance to Shape (15-20 min)**

* Have students turn to page 2 and reintroduce today’s goal: On each side of the opaque box is a radar sensor and data display. Inside the box is a unique three-dimensional shape. Without looking inside the box, it will be up to you and your classmates to determine the shape that lies within using the radar setup.
* Explain that each side of the box is looking at a different axis with regard to the item within. Similar to a graph that you might see in math class, we can see that two of the axes are x and y. The X and Y axes help to give a 2-dimensional view, so to add that third dimension, we use the Z-axis which moves up off of the table.
	+ Have students circle their axis on their handout. Z axis is groups on the left side of the box, X axis is groups in front of the box, and Y axis is groups on the right side of the box.
* Explain to students that the plastic tie on the outside of their box is their cursor. This is connected to the sensors and will be used to help us determine where we would like our sensor to be placed.
* Instruct students to press the “Part 1” box on their data displays. Explain that this now shows the current distance reading recorded by the radar sensor.
* Instruct students to use their handouts to determine the cursor placement and to record the distance displayed on their screen.
* As students complete their data collection, instruct them to graph the data.
	+ The X axis of the graph will be the cursor placement and the Y axis of the graph will be the distance recorded.
* Once all three groups at a table have created their graphs, have them compare and discuss what shape they think was inside their box.
	+ To help students start, have them compare the X and Y views first. Are the edges straight like we’d see in a rectangle? Do the sides slope at a constant rate to a point like we’d see in a triangle? Are the edges always changing, giving a view similar to that of a circle?
	+ Once they have an idea of the 2D view, add in the Z view. This helps determine the object’s height but also how the shape changes as you move up from the table. Is the distance constant but then changes toward the top, like we might see for a cylinder or rectangular prism? Does the distance slope away like we might see in a cone? Does the distance start further, then get closer in the middle and further again at the top like we might see in a sphere?
* As groups come to their final conclusion about the shape of their object, an instructor can open the lid of the container to take the shape out and reclose the lid.
	+ ***At this point, the instructor should also remove the small table from inside the box to allow for the motion needed in part 2.***

**Part 2: Detecting Motion (15-20 min)**

* Regroup as a class to change the focus.
* Explain to students that radar systems to detect distance are some of the simplest systems we have. But let’s put this in the context of an air traffic controller (ATC). ATCs need to see the planes in their region and prevent them from intercepting. Ask students what problems might happen if they could only see blips on the screen for planes and those are only updated every few seconds. *Click three times to show slide animation.*
	+ It’s harder to determine where each dot is moving toward or how fast. It makes it hard to predict if flight paths will cross.
* Explain that many radar systems can not only detect distance from a sensor but also the velocity of the object. Ask students if they have heard of velocity, what does it make them think of?
	+ Velocity is very similar to speed (how fast something is moving) but also communicates the direction of that motion as well.
* *Progress to next slide.* Explain that the point of the triangle now helps to show the direction that the object is moving. *Click three times to show slide animation.* Explain how even just depicting the direction of the objects can help an ATC to predict motion and possible intersections more quickly.
* So how do these systems detect velocity? By utilizing the Doppler effect. Ask students if they have heard of the Doppler effect before.
	+ Students may have some knowledge of this. This question is to gauge the need for the following demonstration or if students can jump ahead.
* **For those that do not know the Doppler effect, continue here.**
* Explain to students that when waves (sound or electromagnetic) come in contact with a moving object, the reflection can alter the wave shape, particularly the wave’s frequency.
* Ask for one volunteer from each table. Have them stand at their table, making sure the stool is no longer in the way. Explain that their role is to pass the provided ball back and forth around the room. Students don’t have to go quickly or pelt each other, we just want the ball to move back and forth in the room.
* Explain to the class that inside the ball is a buzzer that will create a loud sound at a constant frequency, or pitch. Instruct class members to listen to the sound of the buzzer as it moves in the room.
* Instruct the volunteers to start throwing the ball back and forth. After 2-3 roundtrip throws ask the class if they noticed anything about the buzzer sound.
	+ As the ball went away from them the pitch went down, but as it got closer the pitch went up.
* *Use slide to help explain this effect visually.* Explain that when an object emits waves, in this case sound waves, if it were to stay in one place the waves would emit at a constant frequency in all directions (see depiction on the left). But in the case of a moving object, the frequency is higher on the side the object is moving toward and lower on the side the object is moving away from.
* *Use next slide to explain this effect for reflected waves.* Now the same is true for reflected waves, if a wave hits an object in motion we would still expect a higher frequency to be returned if the object is moving in the direction of the wave source (Radar transmitter).
* **If students do know the Doppler effect, jump here.**
* Have students turn to page 3. Explain to students that in this next section, we will be using the radar sensors to determine the path of motion of an object.
* Instruct students to press the “Main Menu” button on their data display.
	+ They may need to hold the button for 1-2 seconds.
* Instruct students to flip the switch at the back of their radar box. Explain that this sets an object in repeated motion. Students should be able to hear something moving inside.
* Explain that in this next section our radar system has been updated to report back many different data points. It will now tell us the time that has elapsed since we started data collection, the distance of the object, and the velocity of the object. If the back of the opposite wall is detected (ie there is no object in the path), the system will not record data.
	+ Explain that in our radar system, positive velocities indicate motion away from the TV screens (away from the back of the radar box) and negative velocities indicate motion toward the TV screens (toward the back of the radar box). They can also measure velocities toward and away from the sensor itself. Moving toward the sensor would be positive and moving away from the sensor would be negative.
* Explain to students to best determine the path of motion, each side of the box will set up their sensor at a specified cursor location. By keeping our sensors static, we can better record when an object crosses its path.
* Instruct students to set their cursor to the defined locations. X at 8cm, Y at 12cm, and Z at 12cm.
* Then instruct students to press the “Part 2” box on their data display all at the same time to begin data collection.
* Inform students that the data display will only show the first 6 readings. This is the first 6 times the sensor detected an object in its path.
* Instruct students to record their results on page 3 of their handout.
* Once the data has been recorded, have students flip the switch in the back of the box to the off position.
* Have students at the tables compare their recorded data. Ask them to think about what is similar and what is different.
	+ Make sure the time readings are taken into consideration. Though all groups will get 6 readings, some groups may get those readings faster than others.
	+ Students in the X group should see twice as many readings in the same period of time.
	+ Students in the X and Y group should see that some of their readings occur at the same time points.
	+ Students in the Y and Z groups should see that their readings occur shortly after one another.
* Instruct students to work together to think about what path the object might have been taking.
	+ Inform students that the path of the object repeated multiple times but it had a planned path. If needed, inform students that the object started at the back of the radar box.
* After 3-5 minutes, discuss this as a group.
* Ask students what they would expect to see as a result if the object only moved linearly (in a straight line at a constant height, say the height of the x and y sensors).
	+ The X group would constantly get results as it’s always in the path but changing distance toward the sensor and then away when it redirected.
	+ The Y group would get one reading as the object passed its location, then there would be a long wait until it passed the sensor again on its return.
	+ The Z group wouldn’t get any results because it was too high to detect the object.
* Ask students if they think their object was on a linear path.
	+ No because they all got readings and the X group didn’t get constant results.
* Ask students to propose the path they think the object took.
	+ Go from table to table to get each group’s thought process.
* Instruct students to carefully remove the lid of the box and turn the switch at the back to on. Have students look in the box to see the moving components to see if their predictions were correct.
* Ask students how many objects were moving inside the box.
	+ Two. An object moving in an arc and an object moving linearly very low.
* Ask students which object we were able to detect.
	+ Only the bar moving in an arc.
* Ask students why we weren’t able to detect the bar moving linearly.
	+ Because it was below our sensor.

**Part 3: Current Radar System Hurdles (5-10 min)**

* Explain to students that outside of plane detection, radar is often also used by the Department of Defense, for missile detection and interception systems. Explain that many of these radar systems can look in a 360-degree sweep of their location on Earth.
* Ask students what 3-dimensional shape is Earth.
	+ A sphere
* Explain to students that because of the Earth’s shape, our radar systems can only detect objects that are tangential to the position of the system on Earth.
* Ask students what a tangent is in geometry.
	+ A line touching, but not intersecting, a curve or curved surface
* *Show depiction with slide.* Explain to students that our radar system can see out over the Earth’s surface for some distance but can also pass outside the Earth’s atmosphere into space.
* *Show depiction with slide (same as in their handout)*. Instruct students to review the image provided and answer the following questions with their partner.
* After 3-5 minutes, review the questions with students.
* Ask which will be detected first: the ballistic missile or the hypersonic glider.
	+ The ballistic missile, it crosses the path of the radar detection closer to the launch location than the hypersonic glider.
* Ask students what hypersonics means. Or what it makes them think of?
	+ Students might know hyper means excessive and sonics means sound.
	+ Hypersonic means that an object is moving faster than the speed of sound, precisely it’s traveling more than 5 times the speed of sound.
* Explain that as hypersonic vehicles become more common, we will need radar systems to help us to detect them. Ask students why hypersonic gliders pose issues with our current radar systems.
	+ They almost literally fly under the radar for most of their flight path. This makes it harder to detect and therefore harder to coordinate an interception. By the time we can detect where it is, it’s already traveling too fast for us to track it.
* Ask students how radar could be implemented differently to overcome this challenge.
	+ Answers may include: having radars in space that look downward toward Earth, having more radar systems strategically placed to detect where we think a hypersonic vehicle might come from,

**Wrap Up (5 minutes)**

* As students are getting ready to leave, remind students that radar or its iterations (ultrasound, sonar, and lidar) have applications that relate to their interests.