

Bermuda Deepwater Caves:  
Dive of Discovery

# Doppler Designs



Image captions/credits on Page 2.

## lesson plan

### Focus

Current measurements using the Doppler effect

### Grade Level

9-12 (Physical Science/Physics)

### Focus Question

How can ocean explorers measure and record currents over extended periods of time?

### Learning Objectives

- Students will explain the Doppler effect.
- Students will describe how the Doppler effect can be used to measure current velocity.

### Materials

- Copies of *Doppler Designs Worksheet, Parts A & B*, one copy for each student group

### Audio-Visual Materials

- (Optional) Interactive white board, computer projector or other equipment for showing images of underwater caves

### Teaching Time

One or two 45-minute class periods

### Seating Arrangement

Groups of two to four students

### Maximum Number of Students

32

### Key Words

Doppler effect  
Current

### Background Information

*NOTE: Explanations and procedures in this lesson are written at a level appropriate to professional educators. In presenting and discussing this material with students, educators may need to adapt the language and instructional approach to styles that are best suited to specific student groups.*



Entrance to one of Bermuda's caves. Image Courtesy of Bermuda: Search for Deepwater Caves 2009 Exploration.

#### Images from Page 1 top to bottom:

The peracarid crustacean order Mictacea is represented by only a single species, *Mictocaris halope*, from inland marine caves in Bermuda. Image courtesy Bermuda: Search for Deepwater Caves 2009.

<http://oceanexplorer.noaa.gov/explorations/09bermuda/media/caves.html>

Overhead view of Bermuda showing the island and the reef platform. Photo courtesy of Bermuda Zoological Society.

<http://oceanexplorer.noaa.gov/explorations/09bermuda/media/bda.html>

Divers swim between massive submerged stalagmites in Crystal Cave, Bermuda. Such stalactites and stalagmites were formed during glacial periods of lowered sea level when the caves were dry and air-filled. Image courtesy of Bermuda: Search for Deepwater Caves 2009.

[http://oceanexplorer.noaa.gov/explorations/09bermuda/background/bermudaorigin/media/bermudaorigin\\_3.html](http://oceanexplorer.noaa.gov/explorations/09bermuda/background/bermudaorigin/media/bermudaorigin_3.html)

Ostracods are small, bivalve crustaceans that can inhabit underwater caves. The ostracod genus *Spelaeoecia* is known only from marine caves and occurs in Bermuda, the Bahamas, Cuba, Jamaica and Yucatan (Mexico). Image courtesy of Bermuda: Search for Deepwater Caves 2009.

<http://oceanexplorer.noaa.gov/explorations/09bermuda/background/plan/media/spelaeoecia.html>

Anchialine caves are partially or totally submerged caves that are located within a few kilometers inland from coastal areas. Anchialine (pronounced "AN-key-ah-lin") is a Greek term meaning "near the sea," and anchialine caves often contain freshwater and/or brackish water in addition to seawater. These caves may be formed in karst landscapes as well as in rock tubes produced by volcanic activity. Karst landscapes are areas where limestone is the major rock underlying the land surface, and often contain caves and sinkholes formed when acidic rainwater dissolves portions of the limestone rock. Water in anchialine caves tends to stratify according to salinity, with the heavier seawater below the level of fresh and brackish water. This stratification produces distinctive habitats occupied by a variety of species that are endemic to these environments (endemic means that these species are not found anywhere else). Some of these species are "living fossils" known as relict species, which means that they have survived while other related species have become extinct.

Animals that live only in anchialine habitats are called stygofauna or stygobites. Investigations of these species have revealed some puzzling relationships, including:

- Some stygobite species appear to have been in existence longer than the caves they inhabit, which implies that these species must have arrived in the caves from somewhere else; but how could this happen if these species are only found in caves?
- Some stygobite species are found in caves that are widely separated, such as certain crustacean species found in caves on opposite sides of the Atlantic Ocean and certain species in Australian anchialine caves that are also found in Atlantic and Caribbean caves.
- Geographic distribution of some species suggests a possible connection with mid-ocean ridges, such as shrimps belonging to the genus *Procaris* that are only known from anchialine habitats in the Hawaiian Islands, Ascension Island in the South Atlantic, and Bermuda in the North Atlantic.
- Some anchialine species are most closely related to organisms that live in the very deep ocean.
- Some anchialine species are most closely related to organisms that live in deep-sea hydrothermal vent habitats.
- An unusually large proportion of anchialine cave species in Bermuda are endemic to these caves, suggesting that these habitats have been stable for a long period of time.

Most investigations of anchialine caves have been confined to relatively shallow depths; yet, the observations described above suggest that connections with deeper habitats may also be important to understanding the distribution of stygobite species. Bermuda is a group of mid-ocean islands composed of limestone lying on top of a volcanic seamount. Because these islands are karst landscapes, Bermuda has one of the highest concentrations of cave systems in the world. Typical



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effect: <http://lectureonline.cl.msu.edu/~mmp/applist/doppler/d.htm>

(d) Review questions on Parts A and B of the *Doppler Designs Worksheet*.

2. Briefly introduce the Bermuda Deepwater Caves 2011: Dive of Discovery Expedition. Tell students that Bermuda has an unusually large number of species living in marine caves that are not found anywhere else, and that some are called "living fossils" because they have survived while other related species have become extinct. Say that very little is known about deepwater marine caves, and discuss why scientists might want to find and explore these caves. Briefly describe how anchialine caves may be formed. Tell students that high-resolution multibeam sonar was used in 2009 to produce detailed maps of the entire shelf edge around the Bermuda Platform in water depths greater than 150 m, and that sites selected from these maps were explored and photographed using an underwater robot called a remotely operated vehicle (ROV).



Show the image referenced in Step 1(b), and call attention to the shiny metal object, black cylinder, and the diving weights attached with cable ties to the plastic pipe frame. Ask students what they think the entire assembly is supposed to do. This image illustrates one of the major activities planned for the 2011 Expedition: further exploration of some caves by human divers who will collect biological specimens and install instruments to measure currents, temperature, and chemical conditions (salinity, pH, dissolved oxygen and chlorophyll concentration) inside the caves. Invite students to speculate about the purpose of the shiny object and the cylinder. The black cylinder is called a sonde, and contains instruments for measuring and recording physical and chemical parameters.

A cave diver placing a Doppler current meter in a submarine cave. Image courtesy Bermuda: Search for Deepwater Caves 2009. [http://oceanexplorer.noaa.gov/explorations/09bermuda/background/hires/doppler\\_hires.jpg](http://oceanexplorer.noaa.gov/explorations/09bermuda/background/hires/doppler_hires.jpg)

The shiny object is a Vector Doppler current meter. Tell students that they are about to investigate how this instrument uses sound waves to measure currents.

[This image is also a good illustration of the advantage of making these measurements with unattended instruments: A lot of suspended sediment is evident in the image, some of which may have resulted from motion of the diver. Even with extreme care, the presence of the diver may affect conditions inside the cave and make it difficult to measure conditions that normally exist.]

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3. Provide each student group with a copy of Part A of the *Doppler Designs Worksheet*, which is a review of basic concepts related to waves. When students have completed Part A of the *Worksheet*, lead a discussion of their answers, which should include:

- Waves are energy transport phenomena. When a wave appears

to move, we are seeing a disturbance moving through a solid, liquid, or gaseous medium. The only thing that is actually transported from one place to another is the energy of the wave.

- A sound wave is an example of a mechanical wave, which requires a medium through which energy can be transferred. You may want to point out that electromagnetic waves do not require a medium, because their energy is transferred as electric and magnetic fields. Electromagnetic waves can also be thought of as the motion of massless packets of energy called photons which move at the speed of light.
- Crest and trough are terms that identify the extremes of displacement experienced by a particle moving in a wave. The crest is the maximum upward or positive displacement of a particle compared to its resting position. The trough is the maximum downward or negative displacement of a particle compared to its resting position.
- The frequency of a wave is the number of complete waves that pass a given point in a certain amount of time, usually one second. Counting the number of crests that pass a certain point in a measured amount of time is one way to find the frequency of the waves.
- The wavelength of a wave is the distance over which a wave's shape repeats. That is, the distance between two adjacent crests.
- The speed of a series of waves is equal to the frequency of the waves multiplied by their wavelength:  
$$C = W \cdot F$$
where C is the speed of the wave, W is wavelength in meters per wave, and F is frequency in hertz (waves per second). The speed of sound waves depends upon the density of the medium through which the waves travel. Notice that at a constant speed, wavelength decreases as frequency increases.
- When we hear sound waves, changes in pitch are the result of changes in frequency; when the frequency of sound waves increases, we perceive this change as a higher pitch. Sound waves that we perceive as having a higher pitch have a shorter wavelength than sound waves with a lower pitch.

4. Perform a demonstration to illustrate the Doppler effect. Two common demonstrations are to tie a small buzzer onto a string approximately 2 m long, stand in the center of the classroom, and whirl it over your head. An alternative is to put the buzzer inside a soft ball (such as a tennis ball or nerf ball), and then toss it to



*Christian Doppler*

<http://www.dspace.cam.ac.uk/bitstream/1810/219142/2/Rb1057J.jpg>

**Who Was Doppler?**

The Doppler effect is named after Christian Doppler, who was born in Salzburg, Austria in 1803. He became a mathematics professor and in 1842 suggested that this effect might result in changes in the apparent color of stars. An early demonstration of the effect applied to sound was performed in 1845 by the Dutch meteorologist Christoph Buys-Ballot. For this demonstration, several trumpeters were assembled aboard a train and played a single note while other musicians stood beside the track and listened as the train approached and passed by.

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various students. In both demonstrations, students should observe that the pitch of the buzzer appears to increase as it moves toward them, and decrease as it moves away.

Ask students what they think is happening to cause this effect. Students should recognize that the effect is observed when the distance between the source of sound and the observer changes. Remind students about the relationship between frequency and wavelength and ask what happens to wavelength as frequency increases. Since increased frequency means decreased wavelength, what could be happening to cause shorter wavelength? At this point, you may want to show the applet referenced in Step 1(c). Students should eventually infer that the sound waves are being compressed as the source of sound moves toward an observer, and that the waves are being extended as the source of sound moves away. Be sure students understand that the frequency of sound produced by the buzzer does not change, and that we perceive a different frequency because the position of the buzzer is changing relative to the observer. Tell students that this perceived change is called Doppler shift, or the Doppler effect, and remind them once again that this is a shift in the OBSERVED frequency and not a shift in the ACTUAL frequency at which the source vibrates.

- 5. Ask students to think of examples in which some environmental characteristic is measured by observing some effect of this characteristic, rather than directly measuring the characteristic itself. For example, temperature is a characteristic that results from the energy contained in materials. We rarely measure this energy directly. Instead, we measure some effect of this energy such as the expansion of a liquid in a thermometer. This is an example of a proxy, which is a person or thing that substitutes for another person or thing. Proxies are often used in scientific investigations when there is a known relationship between two things that makes it possible to measure one to predict the measurement of the other. Tree rings are another example: the number of tree rings is a proxy for the age of the tree, and the distance between rings can be a proxy for climatic conditions during the year when the rings were formed.

Ask students to brainstorm ways that the Doppler effect might be used as a proxy to estimate the strength of currents in water. This activity may be done as a class discussion, or in groups of two to four students. For purposes of this assignment, students may assume that the ratio of the Doppler shift to the frequency of the sound source is equal to the velocity between the sound source and the observer divided by the speed of sound in water:

$$F_d / F_s = V / C$$

where  $F_d$  is the Doppler shift frequency,  $F_s$  is the frequency of the

sound source when nothing is moving,  $V$  is the relative velocity between the sound source and the observer (m/sec), and  $C$  is the speed of sound (m/sec). So, if the observer is stationary, the current velocity could be determined as

$$V = (F_d / F_s) \cdot C$$

After brainstorming, discuss students' ideas. Guide this discussion as necessary to establish the idea that if we have:

- A sound source whose frequency is known;
  - Something moving in a water current that can reflect sound from this source;
  - A way to listen to echoes from the sound reflector; and
  - A way to measure the frequency of the echoes,
- then we can measure the Doppler effect as the difference between the frequency of the source sound and the frequency of the echoes, and use this measurement to estimate current velocity.

Students should realize that this situation is different from the buzzer demonstration. In the demonstration, sound travelled from the source to the observer, and the Doppler shift is

$$F_d = F_s \cdot (V / C)$$

(from the first equation above).

But, in case of current measurements, sound travels from the source to a reflector, and then back to the observer (assuming the device for listening to echoes is in the same place as the sound source). So the Doppler shift happens as the sound is travelling away from the source, and again as the echo travels to the listening device. So the Doppler shift is doubled, and the equation must be changed to:

$$F_d = 2 \cdot F_s \cdot (V / C)$$

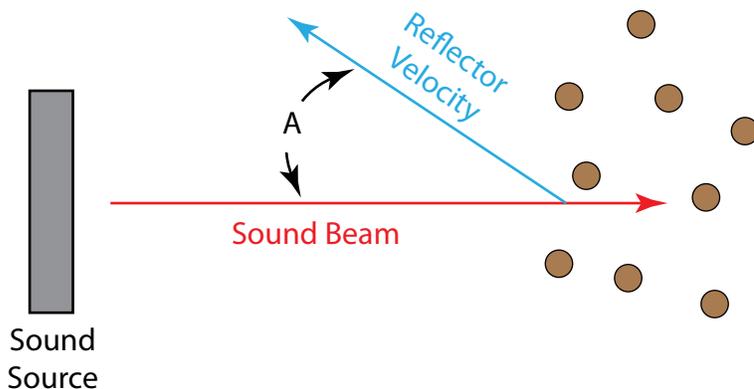
6. Provide each student group with a copy of Part B of the *Doppler Designs Worksheet*. If time permits, you may want to have students create and present their projects to explain the Doppler effect. Prior to these presentations, discuss students' answers to questions in Part B:

- In the ocean, the reflectors for our hypothetical current-measuring instrument are particles suspended in the water. These are usually zooplankton, but may also be suspended sediment or small bubbles.
- A key assumption is that the reflectors move at the same velocity as the currents we want to measure. Experience with Doppler sensors has shown that this assumption is valid.

- If reflectors are moving at an angle to the direction of the sound waves (Worksheet Part B, Figure 1), the vector component that is parallel to the direction of the sound waves is:

$$F_d = 2 \cdot F_s \cdot (V/C) \cdot \cos(A)$$

Figure 1



Since currents move in three dimensions, current measurements based on the Doppler effect require a minimum of three sound beams to measure the x-, y-, and z- vector components. The image of the Vector Doppler current meter referenced in Step 1(b) shows three arms, each containing a transducer (similar to a speaker) that receives echoes from sound beams transmitted from a fourth transducer located at the center of the instrument. The three Doppler shift measurements from the three receiving transducers are mathematically combined to estimate the current direction and velocity. The Vector Doppler current meter is capable of making up to 84 of these measurements per second. Each measurement is recorded in an electronic memory, and may be retrieved when the meter is recovered by divers.

### The BRIDGE Connection

[www.vims.edu/bridge/](http://www.vims.edu/bridge/) - In the "Search" window on the left, type "currents" for links to resources about ocean currents.

### The "Me" Connection

Have students write a brief essay describing at least three ways in which they make personal use of proxies to obtain information about their environment.

### Connections to Other Subjects

Mathematics, Earth Science

### Assessment

Written reports and class discussions provide opportunities for assessment.

### Extensions

1. Visit <http://oceanexplorer.noaa.gov/explorations/11bermuda/welcome.html> for more about the Bermuda Deepwater Caves 2011: Dive of Discovery Expedition.
2. See <http://www.astrocappella.com/doppler.shtml> for a musical explanation of the Doppler effect in astronomy, and a great example of using fine arts to explain science!

### Multimedia Discovery Missions

<http://oceanexplorer.noaa.gov/edu/learning/welcome.html>

Click on the link to Lesson 15 for interactive multimedia presentations and Learning Activities on Seamounts.

### Other Relevant Lesson Plans from NOAA's Ocean Exploration Program

#### Now Take a Deep Breath

(14 pages, 548 Kb) (from the Submerged New World 2009 Expedition)  
<http://oceanexplorer.noaa.gov/explorations/09newworld/background/edu/media/breath.pdf>

Focus: Physics and physiology of SCUBA diving (Physical Science/Life Science)

Students define Henry's Law, Boyle's Law, and Dalton's Law of Partial Pressures, and explain their relevance to SCUBA diving; discuss the causes of air embolism, decompression sickness, nitrogen narcosis, and oxygen toxicity in SCUBA divers; and explain the advantages of gas mixtures such as Nitrox and Trimix and closed-circuit rebreather systems.

#### My Wet Robot (300kb)

(9 pages, 300 Kb) (from the Bonaire 2008: Exploring Coral Reef Sustainability with New Technologies Expedition)  
<http://oceanexplorer.noaa.gov/explorations/08bonaire/background/edu/media/wetrobot.pdf>

Focus: Underwater robotic vehicles (Earth Science)

Students discuss the advantages and disadvantages of using underwater robots in scientific explorations, identify key design requirements for a robotic vehicle that is capable of carrying out specific exploration tasks, describe practical approaches to meet identified design requirements, and (optionally) construct a robotic vehicle capable of carrying out an assigned task.

**No Escape**

(12 pages, 1Mb) (from the 2006 Exploring Ancient Coral Gardens Expedition)

<http://oceanexplorer.noaa.gov/explorations/06davidson/background/edu/escape.pdf>

Focus: Fate of benthic invertebrate larvae in the vicinity of seamounts (Earth Science)

Students use field data to evaluate an hypothesis about the influence of a water circulation cell on the retention of benthic invertebrate larvae in the vicinity of a seamount, and describe some potential advantages and disadvantages to species whose larvae are retained in the vicinity of seamounts where the larvae are produced. Students will also describe the consequences of partial or total larval retention on the biological evolution of species producing these larvae.

**Round and Round**

(11 pages, 1Mb) (from the Mountains in the Sea 2003 Expedition)

[http://oceanexplorer.noaa.gov/explorations/03mountains/background/education/media/mts\\_round.pdf](http://oceanexplorer.noaa.gov/explorations/03mountains/background/education/media/mts_round.pdf)

Focus: Circulation cells in the vicinity of seamounts (Earth Science)

Students interpret data from a three-dimensional array of current monitors to infer an overall pattern of water circulation, hypothesize what effect an observed water circulation pattern might have on seamount fauna that reproduce by means of floating larvae, and describe the importance of measurements to verify theoretical predictions.

**Living in Extreme Environments**

(12 pages, 1Mb) (from the Mountains in the Sea 2003 Expedition)

[http://oceanexplorer.noaa.gov/explorations/03mountains/background/education/media/mts\\_extremeenv.pdf](http://oceanexplorer.noaa.gov/explorations/03mountains/background/education/media/mts_extremeenv.pdf)

Focus: Biological Sampling Methods (Biological Science)

Students understand the use of four methods commonly used by scientists to sample populations; understand how to gather, record, and analyze data from a scientific investigation; begin to think about what organisms need in order to survive; and understand the concept of interdependence of organisms.

## Other Resources

*The Web links below are provided for informational purposes only. Links outside of Ocean Explorer have been checked at the time of this page's publication, but the linking sites may become outdated or non-operational over time.*

<http://oceanexplorer.noaa.gov/explorations/11bermuda/welcome.html> – Web site for the Bermuda Deepwater Caves 2011: Dive of Discovery Expedition

<http://oceanexplorer.noaa.gov/explorations/09bermuda/welcome.html> – Web site for the Bermuda: Search for Deepwater Caves 2009 Expedition

<http://celebrating200years.noaa.gov/edufun/book/welcome.html#book> - A free printable book for home and school use introduced in 2004 to celebrate the 200th anniversary of NOAA; nearly 200 pages of lessons focusing on the exploration, understanding, and protection of Earth as a whole system

Gordon, R. L. 1996. Acoustic Doppler Current Profiler Principles of Operation A Practical Primer. RD Instruments. San Diego, California; available online at [http://comm-tec.com/Library/Technical\\_Papers/RDI/Broadband%20Primer.pdf](http://comm-tec.com/Library/Technical_Papers/RDI/Broadband%20Primer.pdf)

<http://www.tamug.edu/cavebiology/index2.html> – Web site, Anchialine Caves and Cave Fauna of the World

<http://www.goodearthgraphics.com/virtcave/index.html> – Virtual Cave Web site

Iliffe, T. M. and L. S. Kornicker. 2009. Worldwide diving discoveries of living fossil animals from the depths of anchialine and marine caves. *Smithsonian Contributions to Marine Sciences* 38:269-280; available online at <http://www.tamug.edu/cavebiology/reprints/Reprint-195.pdf>

## National Science Education Standards

### Content Standard A: Science As Inquiry

- Abilities necessary to do scientific inquiry
- Understandings about scientific inquiry

### Content Standard B: Physical Science

- Structure and properties of matter
- Motions and forces
- Interactions of energy and matter

### Content Standard E: Science and Technology

- Abilities of technological design

## Ocean Literacy Essential Principles and Fundamental Concepts

### Essential Principle 2.

#### **The ocean and life in the ocean shape the features of the Earth.**

*Fundamental Concept c.* Erosion—the wearing away of rock, soil and other biotic and abiotic earth materials—occurs in coastal areas as wind, waves, and currents in rivers and the ocean move sediments.

*Fundamental Concept e.* Tectonic activity, sea level changes, and force of waves influence the physical structure and landforms of the coast.

### Essential Principle 5.

#### **The ocean supports a great diversity of life and ecosystems.**

*Fundamental Concept e.* The ocean is three-dimensional, offering vast living space and diverse habitats from the surface through the water column to the seafloor. Most of the living space on Earth is in the ocean.

*Fundamental Concept f.* Ocean habitats are defined by environmental factors. Due to interactions of abiotic factors such as salinity, temperature, oxygen, pH, light, nutrients, pressure, substrate and circulation, ocean life is not evenly distributed temporally or spatially, i.e., it is “patchy”. Some regions of the ocean support more diverse and abundant life than anywhere on Earth, while much of the ocean is considered a desert.

### Essential Principle 7.

#### **The ocean is largely unexplored.**

*Fundamental Concept a.* The ocean is the last and largest unexplored place on Earth—less than 5% of it has been explored. This is the great frontier for the next generation’s explorers and researchers, where they will find great opportunities for inquiry and investigation.

*Fundamental Concept b.* Understanding the ocean is more than a matter of curiosity. Exploration, inquiry and study are required to better understand ocean systems and processes.

*Fundamental Concept d.* New technologies, sensors and tools are expanding our ability to explore the ocean. Ocean scientists are relying more and more on satellites, drifters, buoys, subsea observatories and unmanned submersibles.

*Fundamental Concept f.* Ocean exploration is truly interdisciplinary. It requires close collaboration among biologists, chemists, climatologists, computer programmers, engineers, geologists, meteorologists, and physicists, and new ways of thinking.

### Send Us Your Feedback

In addition to consultation with expedition scientists, the development of lesson plans and other education products is guided by comments and suggestions from educators and others who use these materials. Please send questions and comments about these materials to:

[oceaneducation@noaa.gov](mailto:oceaneducation@noaa.gov).

### For More Information

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### Credit

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## Doppler Designs Worksheet

### Part A: Basic Concepts About Waves

1. When we see a wave, something appears to be moving. Does this motion involve transporting something from one place to another?

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2. Sound waves require a medium through which the wave can move. What is the name for this type of wave?

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3. What do the terms crest and trough mean?

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4. What is the frequency of a wave?

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5. What is the wavelength of a wave?

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6. What is the relationship between wavelength, frequency, and the speed of a series of waves?

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7. When we hear sound waves, what causes changes in the pitch of the sound we hear?

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**Part B:**

1. What objects in the ocean could be the reflectors for our hypothetical current-measuring instrument?

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2. What do we have to assume about the relationship between the reflectors and currents for our hypothetical current-measuring method to work?

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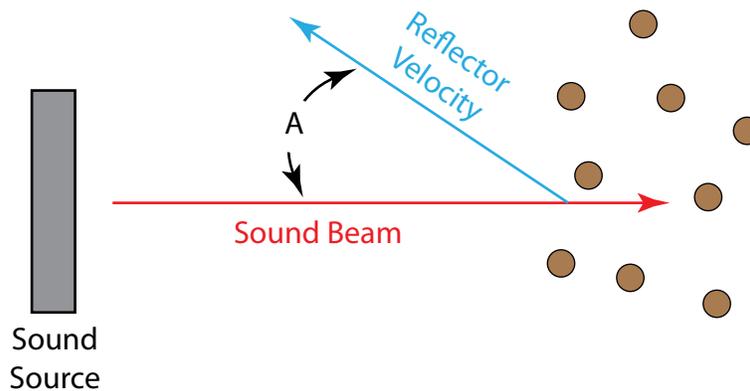
3. Our formula that relates Doppler shift to current velocity is

$$F_d = 2 \cdot F_s \cdot (V/C)$$

But this formula will only work if the reflectors are moving parallel to the direction of the sound beam. Suppose the reflectors are moving at an angle to the direction of the sound beam as shown in Figure 1. How could you modify the formula to account for this angular motion?

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**Figure 1**

4. Design a project to explain how the Doppler effect works. This may be a physical demonstration, cartoon, musical product, or any other format suitable for presentation in your classroom.