

Watching in 3D

Focus

Multibeam sonar

Grade Level

9-12 (Physical Science/Earth Science); also see note concerning grades 6-8 Earth Science under *Next Generation Science Standards and Ocean Literacy Essential Principles and Fundamental Concepts*

Focus Question

How is multibeam sonar used to explore Earth's deep ocean?

Learning Objectives

- Students will explain how multibeam sonar uses the properties of sound waves in water for scientific research about the shape and composition of the ocean floor (bathymetry).
- Students will analyze and interpret multibeam sonar data to identify patterns in the distribution of seafloor features that contribute to scientific research about large-scale interactions in Earth's systems.

Materials

- Copies of the *Sonar Background Review Worksheet*, one copy for each student
- Copies of the *Introduction to Multibeam Imagery Worksheet*, one copy for each student group

Audiovisual Materials

- Video projector or large screen monitor for showing downloaded images (see Learning Procedure, Step 3)

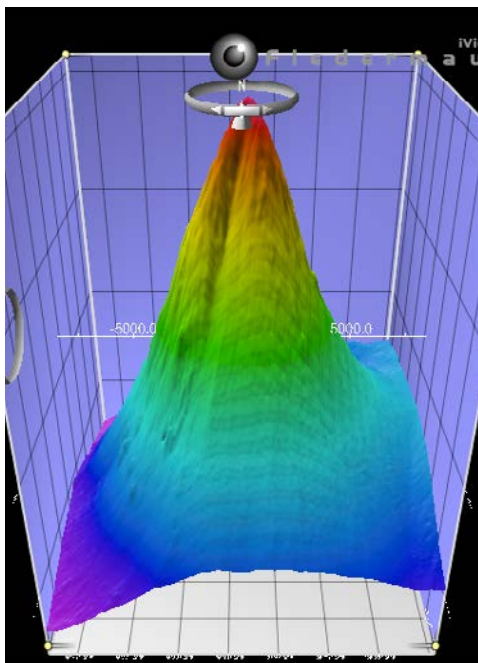
Teaching Time

Two or three 45-minute class periods

Seating Arrangement

Groups of three to four students

The NOAA Office of Ocean Exploration and Research pursues every opportunity to map, sample, explore, and survey at planned destinations as well as during transits; "Always Exploring" is a guiding principle. This image shows the multibeam bathymetry data acquired during the ship's transit west from Oahu to the Johnston Atoll Unit. Image courtesy of the NOAA OER.
<http://oceanexplorer.noaa.gov/oceanos/explorations/ex1706/dailyupdates/media/july11.html>



A multibeam sonar image of the Kawio Barat submarine volcano as viewed in iView4D software and using data collected during the INDEX-SATAL 2010 Expedition.



Mapping personnel on the Discovering the Deep: Exploring Remote Pacific MPAs expedition (L to R): Mapping Lead Derek Sowers, Watch Lead Jason Meyer, and Survey Technician Charles Wilkins. Image courtesy of the NOAA Office of Ocean Exploration and Research, Discovering the Deep: Exploring Remote Pacific MPAs.
<http://oceanexplorer.noaa.gov/oceanos/explorations/ex1703/logs/mar11/welcome.html>

Maximum Number of Students

30

Key Words and Concepts

Ocean Exploration
Okeanos Explorer
Bathymetric map
Multibeam sonar

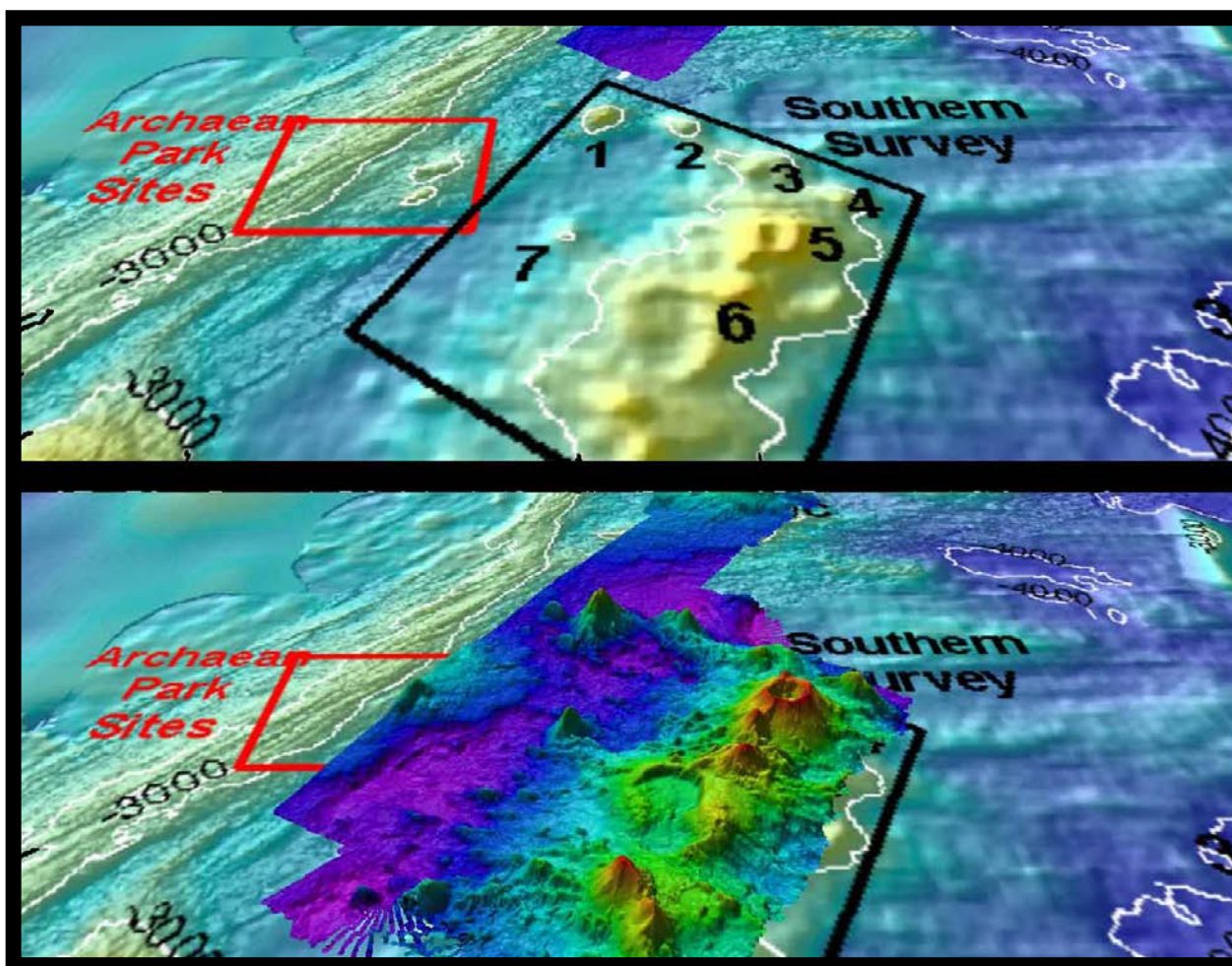
Background Information

Multibeam sonar is one of the most powerful tools available for modern deep-sea exploration, and can create high-resolution maps, three dimensional models, or even “fly-through” videos that simulate a trip across the area being mapped. For more information about multibeam sonar, please see the *Introduction to Multibeam Sonar*.

An important technique for studying multibeam images uses a three-dimensional data visualization system called Fledermaus (which is the German word for “bat,” and is pronounced “FLEEDER-mouse”). This lesson introduces students to multibeam sonar technology and simple analysis of multibeam data using free viewing software for multibeam imagery in the Fledermaus file format. As the NOAA Ship *Okeanos Explorer* and other ships of exploration continue exploring/investigating Earth’s deep ocean, students will have additional opportunities to apply their analytic skills to investigate new multibeam images.

Learning Procedure

1. To prepare for this lesson:
 - a) Review *Ocean Mapping: An Essential Part of Ocean Exploration* by Derek Sowers, Jason Meyer, and Charles Wilkins <http://oceanexplorer.noaa.gov/oceanos/explorations/ex1703/logs/mar11/welcome.html>.
 - b) Review *Introduction to Ships of Exploration and Their Strategy for Ocean Exploration* <http://oceanexplorer.noaa.gov/oceanos/edu/collection/media/hdwe-StrategyBkgnd.pdf>, and *Introduction to Multibeam Sonar* <http://oceanexplorer.noaa.gov/oceanos/edu/collection/media/hdwe-MMBkgnd.pdf>.
 - c) If desired, download images to accompany discussions in Step 2. You may also want to download this “before and after” image to illustrate the capabilities of multibeam sonar: http://oceanexplorer.noaa.gov/oceanos/explorations/10index/background/hires/em302_before_after_hires.jpg, and <http://oceanexplorer.noaa.gov/oceanos/explorations/ex1703/logs/mar11/welcome.html>, as well as the following animation to accompany discussions in Step 3: http://oceanexplorer.noaa.gov/oceanos/media/movies/ex_podcast_video.html
 - d) Review background information on multibeam sonar technology and questions on the *Sonar Background Review*



and *Introduction to Multibeam Imagery Worksheets* and make copies of *Sonar Background Review Worksheet* for each student, and copies of *Introduction to Multibeam Imagery Worksheet* for each student group.

- e) Download the iView4D software from <http://www.qps.nl/display/main/download>. You will need to fill in the contact form, then select the version appropriate to your operating system (Windows, Mac, and Linux versions are available; this download may take some time, so plan ahead!); download the data file **INDEX2010_mb_1.sd** from http://oceanexplorer.noaa.gov/oceanos/edu/resources/media/INDEX2010_mb_1.sd; and install these on computers that students will be using to complete the *Worksheet* activity. Alternatively, you may have students download these resources onto their own computers.

2. Provide each student with a copy of the *Sonar Background Review Worksheet* as homework in preparation for the remainder of this lesson.

This “before and after” image provides a glimpse of *Okeanos Explorer’s* EM302 mapping system capabilities in deep water. The top image shows what we previously knew about the seafloor terrain in the southern Mariana region from satellite altimetry data. The bottom image includes an overlay of the information provided by the ship’s EM302 multibeam system. Image courtesy NOAA Office of Ocean Exploration and Research.

http://oceanexplorer.noaa.gov/oceanos/explorations/10index/background/hires/em302_before_after_hires.jpg

Exploring the Deep Ocean with NOAA



One of the EM302 transducers installed on the hull of the NOAA Ship *Okeanos Explorer* in 2008. Image courtesy NOAA Office of Ocean Exploration and Research.

<http://oceanexplorer.noaa.gov/okeanos/explorations/ex1503/logs/jun6/media/em302.html>



Water samples are collected from the Niskin bottles on the CTD. All 20 Niskin bottles take water samples from various depths, starting near the seafloor and ending close to the surface. Photo courtesy of Caitlin Bailey, GFOE, The Hidden Ocean 2016: Chukchi Borderlands.

<http://oceanexplorer.noaa.gov/explorations/16arctic/logs/july24/media/shipton.html>



Remotely operated vehicle *Deep Discoverer* being recovered. Image courtesy of NOAA Office of Ocean Exploration and Research, 2016 Deepwater Exploration of the Marianas.

<http://oceanexplorer.noaa.gov/okeanos/explorations/ex1605/logs/may1/media/1605rovrecovery.html>

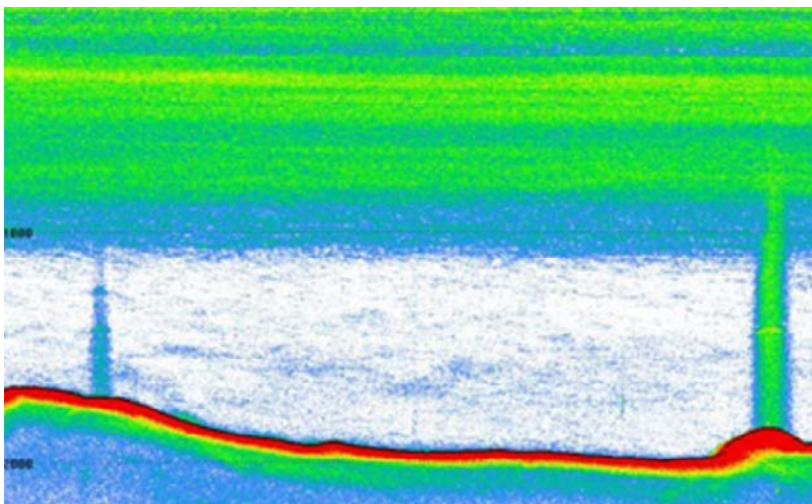


The NOAA Ship *Okeanos Explorer*, America's ship for ocean exploration. Image courtesy NOAA. <http://oceanexplorer.noaa.gov/okeanos/explorations/ex1702/logs/mar1/media/okeanos.html>

3. Briefly introduce the ships of exploration NOAA Ship *Okeanos Explorer*, E/V *Nautilus*, and R/V *Falkor*; the Introduction to Ships of Exploration and Their Strategy for Ocean Exploration <http://oceanexplorer.noaa.gov/okeanos/edu/collection/media/hdwe-StrategyBkgnd.pdf> and the 2017 Discovering the Deep: Exploring Remote Pacific MPAs Expedition <http://oceanexplorer.noaa.gov/okeanos/explorations/ex1703/background/plan/welcome.html>.

Briefly discuss why this kind of exploration is important (for background information, please see the lesson To Boldly Go... http://oceanexplorer.noaa.gov/okeanos/edu/collection/media/wdwe_toboldlygo.pdf. Highlight the overall exploration strategy used by ships of exploration, including the following points:

- The overall strategy is to develop baseline information about the biological, geological, and water chemistry features of unexplored areas to provide a foundation for future exploration and research.
- This information includes:
 - High resolution maps of the area being explored, as well as areas that the ship crosses while underway from one location to the next (underway reconnaissance);
 - Exploration of water column chemistry and other features; and
 - High definition close-up video of biological and geological features in the exploration area (site characterization).
- This strategy relies on four key technologies:
 - Multibeam sonar mapping system and other types of sonar that can detect specific features in the water column and on the seafloor;
 - Conductivity, Temperature, and Depth profilers (CTD) and other electronic sensors to measure chemical and physical seawater properties;
 - A Remotely Operated Vehicle (ROV) capable of obtaining

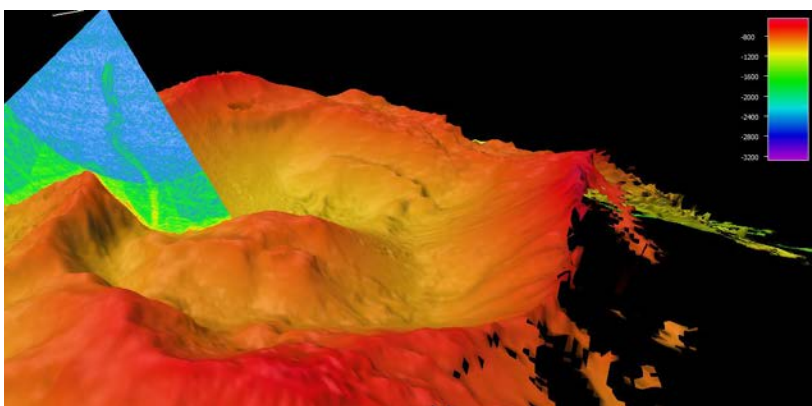


high-quality imagery and samples in depths as great as 6,000 meters; and

- Telepresence technologies that allow scientists with many different areas of expertise to observe and interact with exploration activities, though they may be thousands of miles from the ship.

You may want to show some or all of the images in the adjacent sidebar to accompany this review.

4. Review students' answers to questions on the *Sonar Background Review Worksheet*. These may be compared with the answers provided.
5. Ask students what they know about sonar, and provide additional information as necessary. Be sure students understand that sonar uses an acoustic signal or pulse of sound that is transmitted into the water by a sort of underwater speaker/microphone known as a transducer. If the seafloor or other object is in the path of the sound pulse, the sound bounces off the object and returns an "echo" to the sonar transducer. The time elapsed between the emission of the sound pulse and the reception of the echo is used to calculate the distance of the object. Since the time between transmission of a pulse and the return of its echo is the time



Example image of an echogram from EK60 fisheries sonar. The red feature is the seafloor. Green and blue areas in the water column are features with high backscatter, the lines near the surface show dense layers of biology (zooplankton, fish, gelatinous creatures, etc.), while the vertical lines are bubble plumes emanating from the seafloor. Image courtesy of the NOAA Office of Ocean Exploration and Research, *Discovering the Deep: Exploring Remote Pacific MPAs*.

<http://oceanexplorer.noaa.gov/oceanos/explorations/ex1703/logs/mar11/media/echogram.html>



Picture of the EK60 split-beam transducer mounted on the hull of the *Okeanos Explorer*. Image courtesy NOAA Office of Ocean Exploration and Research.

<http://oceanexplorer.noaa.gov/oceanos/explorations/ex1503/logs/jun6/media/ek60.html>

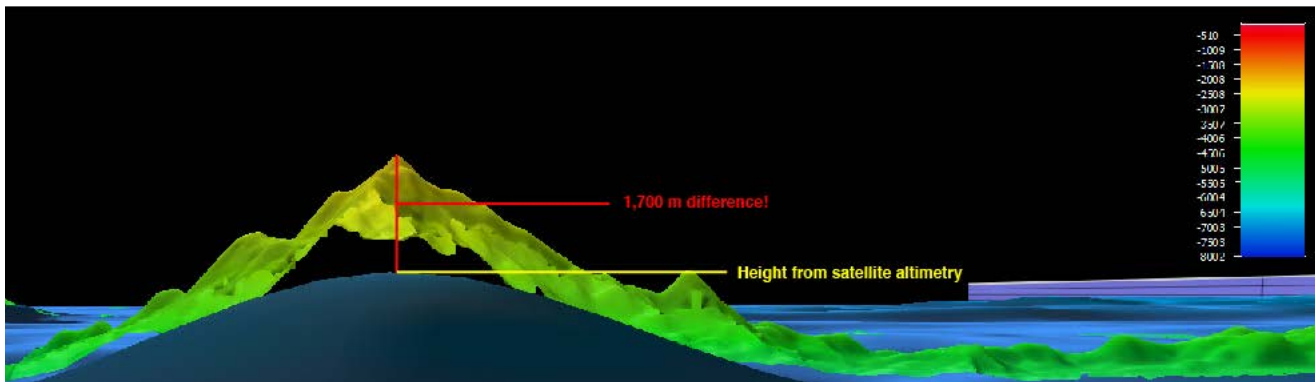


Global Foundation for Ocean Exploration Video Engineer Roland Brian adjusts the zoom, focus, and lighting on remotely operated vehicle *Deep Discoverer's* main HD camera to obtain the best shot of a tiny jellyfish. Image courtesy of the NOAA OER, 2017 *Laulima O Ka Moana*.

<http://oceanexplorer.noaa.gov/oceanos/explorations/ex1706/dailyupdates/media/july27-2.html>

Multibeam sonar imagery shows a plume of bubbles rising from the seafloor at *Vailulu'u Seamount* near American Samoa. Image courtesy of the NOAA 2017 American Samoa Expedition.

<http://oceanexplorer.noaa.gov/oceanos/explorations/ex1702/logs/feb22/media/vailulu2.html>



This image, from a multibeam sonar survey in the Pacific Remote Islands Marine National Monument, shows an approximately 1,700 meter seamount height difference when compared to previous satellite altimetry.

<http://oceanexplorer.noaa.gov/edu/images/WetMapsImageRev.jpg>



Typical night time mapping watch in the control room. Image courtesy NOAA OER.

http://oceanexplorer.noaa.gov/okeanos/explorations/10index/logs/aug05/media/night_watch.html



Physical Scientist Meme Lobecker teaches Indonesian scientist Cecep Sujana how to conduct an XBT cast. The XBT measures temperature through the water column. The XBT software calculates sound velocity, which is applied to the multibeam data for accurate measure of bathymetry.

http://oceanexplorer.noaa.gov/okeanos/explorations/10index/logs/aug05/media/xbt_cast.html

it takes the sound to travel to the bottom and back, if we know this time and the local speed of sound we can calculate the distance to the bottom (this distance is called range). The time measured between pulse transmission and echo return is the “round trip” time, so the pulse has travelled twice the range during this time. For this reason, the general formula for range is:

$$\text{range} = (1/2) (\text{local speed of sound}) (\text{echo time})$$

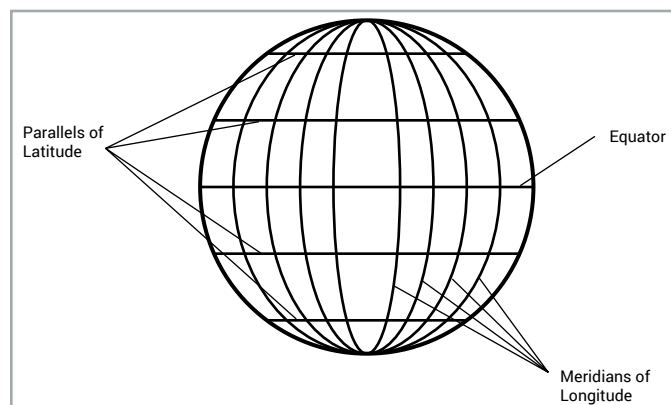
A multibeam sonar system uses multiple transducers pointing at different angles on either side of a ship to create a swath of signals. The time interval between signal transmission and return echo arrival is used to estimate depth over the area of the swath. In addition to high-resolution maps, multibeam data can be used to create three-dimensional models or even “fly-through” videos that simulate a trip across the area being mapped. You may want to show one or more of the images or video clips referenced in Step 1c.

Describe the role of multibeam sonar in ocean exploration aboard *Okeanos Explorer*. The image above shows how much *Okeanos Explorer's* EM302 mapping system adds to what we know about seafloor terrain. <http://oceanexplorer.noaa.gov/edu/images/WetMapsImageRev.jpg>

Students should realize that multibeam and other sonar systems are the key technology for the “reconnaissance” component of the overall exploration strategy, and provides the “big picture” view as scientists explore the sea floor and the water column.

Show this image http://oceanexplorer.noaa.gov/okeanos/explorations/10index/logs/hires/xbt_cast_hires.jpg in which two scientists are conducting an XBT cast during the INDEX-SATAL 2010 Expedition. Be sure students understand that an XBT is an “expendable bathythermograph” which measures temperature through the water column. Ask students why this information is important to accurate multibeam operations. Students should realize that temperature affects the local speed of sound, which we have to know in order to calculate range as described above.

6. Provide each student group with a copy of the *Introduction to Multibeam Imagery Worksheet*, and ensure that students have access to the software and file referenced in Step 1e. Tell students that this activity is intended to familiarize them with multibeam imagery and how it can be manipulated to answer basic questions about features on the ocean floor. You may also want to mention that this skill will enable them to investigate additional images that will be available from future ocean exploration missions.



7. When students have answered the questions on the *Introduction to Multibeam Imagery Worksheet*, lead a discussion of their results. Students' answers may be compared with the answers provided.

The BRIDGE Connection

www.vims.edu/bridge/ – Scroll over “Ocean Science Topics” in the menu on the left side of the page, then “Human Activities,” then click on “Habitats” then select “Deep Ocean” for activities and links about deep ocean ecosystems.

The “Me” Connection

Have students write a brief essay describing a backpacking trip across a landscape having the topography shown in the multibeam image used for the activity in this lesson.

Connections to Other Subjects

English Language Arts, Mathematics, Social Studies

Assessment

Class discussions and students' work with the mapping simulation activity provide opportunities for assessment.

Multimedia Discovery Missions

<http://www.oceanexplorer.noaa.gov/edu/learning/welcome.html>
Click on the links to Lessons 1, 5 and 6 for interactive multimedia presentations and Learning Activities on Plate Tectonics, Chemosynthesis and Hydrothermal Vent Life, and Deep-Sea Benthos.

Other Relevant Lessons from NOAA OER

The Ridge Exploring Robot

<http://oceanexplorer.noaa.gov/explorations/10chile/background/edu/media/robot.pdf>

Focus: Autonomous Underwater Vehicles/Marine Navigation (Grades 9-12; Earth Science/Mathematics)

Latitude and Longitude

If students are not familiar with the concepts of latitude and longitude, see *The Robot Archaeologist* (<http://oceanexplorer.noaa.gov/explorations/09newworld/background/edu/media/robot.pdf>), page 11.

Degrees, Minutes, Seconds or Decimal Degrees?

The iView4D software provides longitude and latitude (x and y “Geo Coords” on the bottom left of the viewer window) in degrees, minutes, and seconds; but the Digital Atlas uses the decimal degree format.

To convert degrees/minutes/seconds to decimal degrees:

1. Convert seconds to minutes, and add to minutes.
2. Convert minutes to degrees, and add to degrees.

For example, to convert 4° 44' 49" to decimal degrees:

1. Divide 49" by 60 seconds/minute = 0.81667; add to 44' = 44.81667'
2. Divide 44.81667' by 60 minutes/degree = 0.74694°; add to 4° = 4.74694°

To convert decimal degrees to degrees/minutes/seconds:

1. Multiply the decimal portion of the number by 60. The whole number portion of the result is minutes.
2. Multiply the decimal portion of the result by 60 to find the number of seconds.

For example, to convert 4.74694° to degrees/minutes/seconds:

1. Multiply 0.74694 by 60 = 44.8164. The number of minutes is 44.
2. Multiply 0.8164 by 60 = 48.984. The number of seconds is 49.

So, 4.74694° = 4° 44' 49"



The Next Generation Science Standards
The Next Generation Science Standards integrate three dimensions within each standard: Science and Engineering Practices, Disciplinary Core Ideas, and Crosscutting Concepts. The standards are written as student performance expectations. While specific performance expectations may emphasize only a few of the practice categories, teachers are encouraged to utilize several practices in any instruction. Similarly, only a few crosscutting concepts may be emphasized, but this is not intended to limit instruction.

Students explain a three-phase strategy that uses an Autonomous Underwater Vehicle (AUV) to locate, map, and photograph previously undiscovered hydrothermal vents; design a survey program to provide a photomosaic of a hypothetical hydrothermal vent field; and calculate the expected position of the AUV based on speed and direction of travel.

Sound Pictures

<http://oceanexplorer.noaa.gov/explorations/10sanandreas/background/edu/media/soundpics912.pdf>

Focus: Sonar (Grades 9-12; Physical Science)

Students explain the concept of sonar, describe the major components of a sonar system; explain how multibeam and side-scan sonar systems are useful to ocean explorers; and simulate sonar operation using a motion detector and a graphing calculator.

Next Generation Science Standards and Ocean Literacy Essential Principles and Fundamental Concepts

This lesson supports the Ocean Literacy Essential Principles and Fundamental Concepts as indicated here <http://oceanexplorer.noaa.gov/oceanos/edu/collection/media/hdwe-Standards.pdf>. Additionally, while it is not intended to target specific Next Generation Science Standards, activities in this lesson may be used to address specific elements of the NGSS as described below.

Specific NGSS Performance Expectation relevant to this lesson is:

MS-ESS2-3. Analyze and interpret data on the distribution of fossils and rocks, continental shapes, and seafloor structures to provide evidence of the past plate motions. [Clarification Statement: Examples of data include similarities of rock and fossil types on different continents, the shapes of the continents (including continental shelves), and the locations of ocean structures (such as ridges, fracture zones, and trenches).] [Assessment Boundary: Paleomagnetic anomalies in oceanic and continental crust are not assessed.]

Discussion about multibeam sonar may be linked to the geographic distribution of underwater volcanoes and how this distribution provides evidence of plate motions.

For Information and Feedback

We value your feedback on this lesson, including how you use it in your formal/informal education settings. Please send your comments to: oceaneducation@noaa.gov

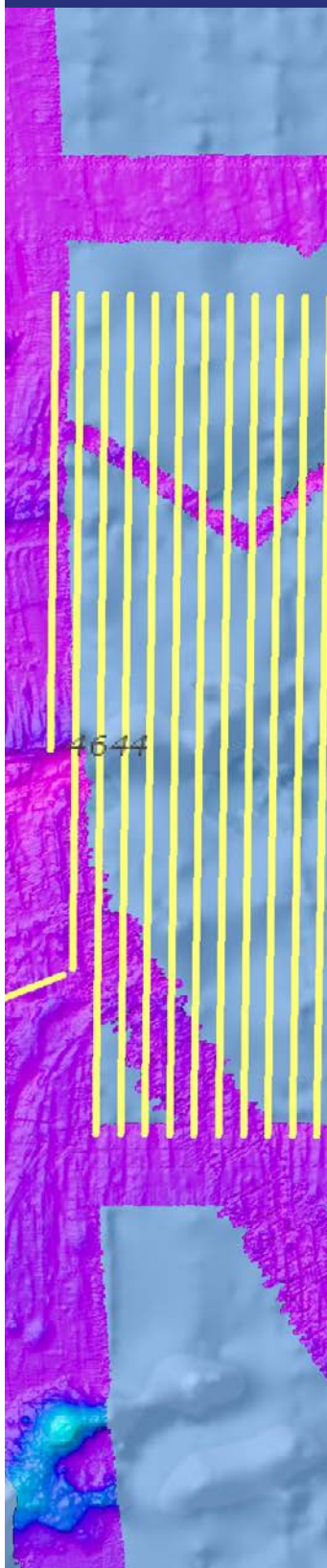
Acknowledgments

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Sonar Background Review Worksheet

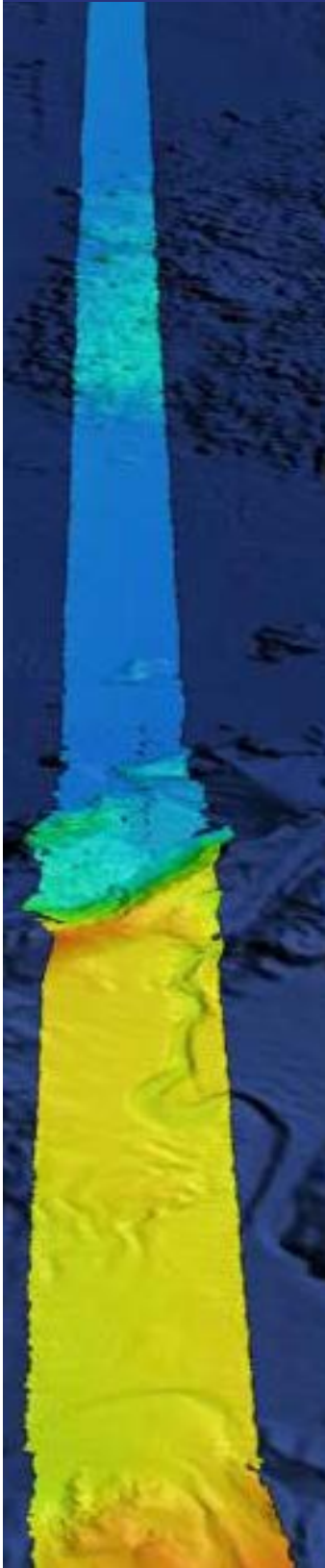
1. How are sound waves in water different from electromagnetic waves such as light or radio waves?
2. What are some conditions that affect the speed of sound waves travelling in water?
3. Sound waves may be thought of as a sequence of moving pressure fronts. What is the term for the physical distance between two consecutive pressure fronts?
4. What is the term for the number of pressure fronts that pass a stationary point in a certain amount of time?
5. What is the mathematical relationship between the properties described in Questions 3 and 4?
6. When a sound wave moving through water encounters a change in temperature, what happens to the properties described in Questions 3 and 4?
7. When a sound wave moves through the water, what is it that is actually moving?
8. Instruments called hydrophones measure the changes in pressure caused by the pressure fronts of a sound wave. If one sound wave is found to cause greater pressure changes than another sound wave, what does this indicate about the two waves?
9. The pressure caused by a sound wave is directly related to a third property of waves. What is this property?
10. What happens to the property identified in Question 9 as a sound wave moves through water?
11. How is the effect identified in Question 10 related to the property identified in Question 4?
12. When a sound wave moving through water encounters another medium, such as rock or sand, what are three things that happen to the quantity identified in Question 7?

Section of map showing planned mapping survey lines in yellow. Publicly available bathymetry in the background downloaded from NOAA's National Centers for Environmental Information archives and collected on various survey platforms. Image courtesy of the NOAA OER. <http://oceanexplorer.noaa.gov/oceanos/explorations/ex1707/media/ex1707-fz.html>



Sonar Background Review Worksheet Answers

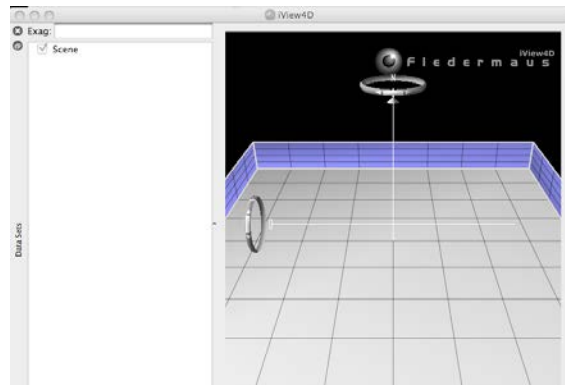
1. Sound waves in water move as compression waves, while electromagnetic waves are transverse waves.
2. The speed of sound waves travelling in water is affected by conditions of the water such as salinity, pressure, and temperature; the speed of sound waves under a particular set of these conditions is called the local speed of sound. In the ocean, the speed of sound is about 1,500 meters per second.
3. The physical distance between two consecutive pressure fronts in a sound wave is wavelength.
4. The number of pressure fronts that pass a stationary point in a certain amount of time is the frequency of the wave.
5. The mathematical relationship between wavelength and frequency is:
$$\text{speed of sound} = \text{frequency} \times \text{wavelength}$$
Typically, wavelength is measured in meters (m), and frequency is measured in cycles per second (Hz), so units for the speed of sound are meters per second.
6. When a sound wave moving through water encounters a change in temperature, the local speed of sound and wavelength change, but frequency remains constant.
7. When a sound wave moves through the water, energy is the thing that actually moves.
8. If one sound wave induces a greater pressure change than another sound wave, the first sound wave contains more energy.
9. The pressure caused by a sound wave is directly related to the amplitude of the wave, which is related to the acoustic energy of the wave; higher amplitude waves contain more energy.
10. When a sound wave moves through water, it gradually loses some of its energy, so its amplitude is reduced.
11. Sound waves with higher frequencies lose energy more rapidly than those with lower frequencies.
12. When a sound wave moving through water encounters another medium, some of its energy is transferred into the new medium, some of it is reflected off the surface of the medium, and the rest is scattered in all directions. How much energy is reflected and how much is scattered depends on the characteristics of the medium and the angle at which the wave strikes the medium (angle of incidence). The energy that is reflected maintains the frequency characteristics of the original sound wave.



Introduction to Multibeam Imagery Worksheet

1. Launch the iView4D software. Your screen should resemble Figure 1. Note the Rotation Control Rings near the top center and mid-left side of the screen. If your screen doesn't look like Figure 1, be sure "Bounds" is checked under the "View" drop-down menu.

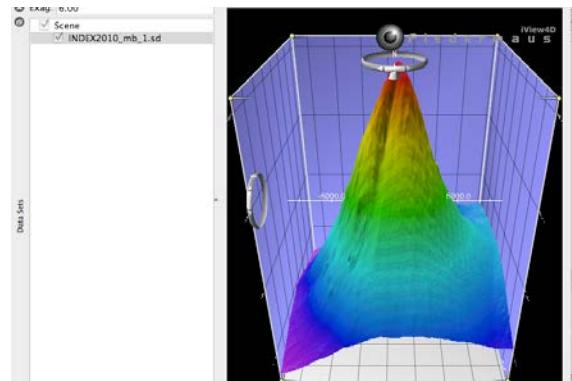
Figure 1.



2. Open the file, **INDEX2010_mb_1.sd**. Now your screen should resemble Figure 2.

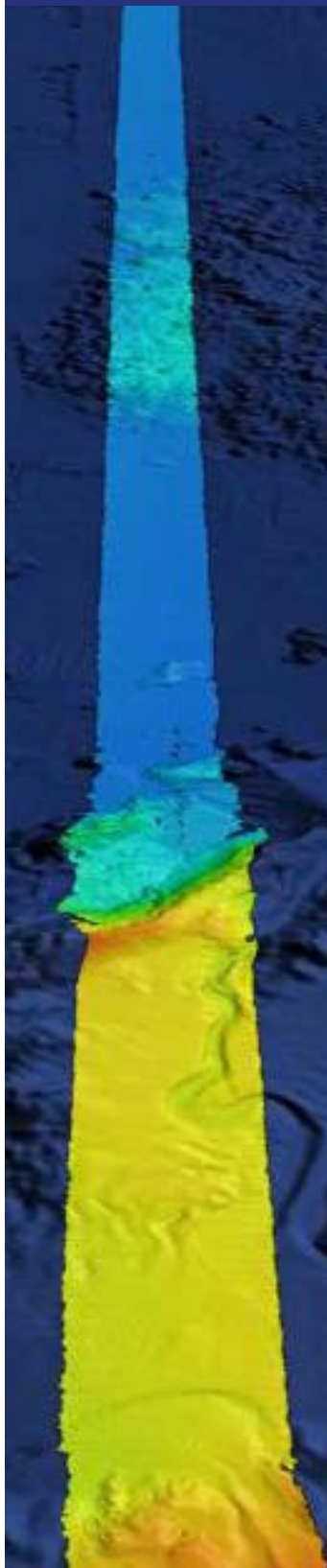
This is a multibeam sonar image of the Kawio Barat submarine volcano which was identified as a priority for exploration during the INDEX-SATAL 2010 Expedition.

Figure 2.



The ocean floor is shown as a three-dimensional image. The x-axis represents longitude, the y-axis represents latitude, and the z-axis represents depth. When you move the cursor over the image, the window

The NOAA Office of Ocean Exploration and Research pursues every opportunity to map, sample, explore, and survey at planned destinations as well as during transits; "Always Exploring" is a guiding principle. Mapping data is collected at all times when the ship is transiting and underway. This image shows the multibeam bathymetry data acquired during the ship's transit west from Oahu to the Johnston Atoll Unit. Image courtesy of the NOAA OER. <http://oceanexplorer.noaa.gov/oceanos/explorations/ex1706/dailyupdates/media/july11.html>



near the bottom of the screen shows the geo coordinates (x, y, and z) for the location beneath the cursor.

The Rotation Control Ring near the top allows you to rotate the image around the vertical axis, and the Rotation Control Ring on the left allows you to rotate the image around the horizontal axis. Alternatively, you can left-click (simple click on a Macintosh platform) and drag up or down to rotate the image around the horizontal axis, or left-click and drag left or right to rotate the image around the vertical axis.

You can zoom the image by right-clicking (or control-clicking on a Macintosh platform) in the middle of the image, then dragging to zoom in or out.

Some images use “vertical exaggeration” to show features more clearly. This means that the vertical scale is larger than the horizontal scale so vertical features are magnified. You can control the amount of vertical exaggeration by clicking and dragging the cone-shaped object on the vertical scale line near the middle of the image. Numbers on the scale lines show the relative horizontal and vertical scales.

Experiment with these controls to find out how they allow you to manipulate the image.

3. Answer the following questions:
 - a. What are the northern and southern latitude boundaries for this image? (Hint: The Rotation Control Ring on the left allows you to rotate the image so that you are looking straight down.)
 - b. What are the eastern and western longitude boundaries for this image?
 - c. The deepest parts of the image are approximately how deep?
 - d. How deep is the shallowest part of this volcano? (Hint: Increasing the vertical exaggeration will make it easier to spot the shallowest portion.)
 - e. What is the approximate diameter of the volcano at its base? (Hint: One minute of latitude is equal to one nautical mile, which is equal to 1.852 km; but note that the squares on the Fledermaus image are not necessarily equal to one minute.)
 - f. What is the approximate slope of the volcano? (Hint: Think of the volcano as a right triangle whose base is one-half the volcano’s diameter.)
 - g. Often, areas where local topography is steep or very changeable will also be areas that have a variety of biological organisms. What is the approximate location of an area on the volcano that seems to have this kind of topography? (Hint: This is easier to see without vertical exaggeration.)

Answers for Multibeam Imagery Worksheet

- a. The northern and southern latitude boundaries for the image are about $4^{\circ} 44' 49''$ (4.7469°) N latitude and about $4^{\circ} 36' 10''$ (4.6028°) N latitude respectively. Reading the numbers on the latitude and longitude scales can be difficult; an easier way to find this information is to rotate the image so that we are directly overhead, then place the cursor near the edges of the image and read the latitude and longitude coordinates from the window on the lower left.
- b. The eastern and western longitude boundaries for this image are about $125^{\circ} 9' 39''$ (125.1608°) E longitude and about $125^{\circ} 01' 02''$ (125.0172°) E longitude, respectively.
- c. The deepest parts of the image are approximately 5,400 meters deep (near the northwestern edge of the image).
- d. The shallowest part of this volcano is about 1,870 meters deep.
- e. We can estimate the diameter of the volcano by finding the north and south latitude boundaries of the base. If we use the edge of the light blue shading as the base (the actual base is deeper than this, but is not completely shown in the image; students may select a different outer boundary, in which case the following calculations will need to be adjusted, but the calculation technique is the same), the northern latitude boundary is about $4^{\circ} 44' 21''$ (4.73917°) N, and the southern latitude boundary is about $4^{\circ} 36' 16''$ (4.60444°) N. The difference between these numbers is $8' 5''$. Since one minute of arc is equal to 60 seconds of arc, 5 seconds is equal to

$$5 \div 60 = 0.083 \text{ minute}$$

So the diameter is approximately 8.083 minutes, which is equal to 8.083 nautical miles, which is equivalent to

$$8.083 \text{ nm} \cdot 1.852 \text{ km} = 14.97 \text{ km}$$

- f. To calculate the approximate slope of the volcano using the triangle hint, we need to know the diameter and height of the volcano. If we continue to use the edge of the light blue shading as the base, the depth at this point is about 4,539 m. Since the shallowest part of the volcano is about 1,870 m, its height is approximately 2,669 m. If the base of the triangle is one-half the volcano's diameter, this is equal to

$$0.5 \cdot 14.97 \text{ km} = 7.485 \text{ km} = 7,485 \text{ m}$$

The slope of the volcano is the angle between the side of the triangle and its base. The tangent of this angle is equal to the height divided by the base:

$$\tan \text{ slope} = 2,669 \text{ m} \div 7,485 \text{ m} = 0.357$$

The arctangent of 0.357 is the angle of the slope, which is equal to 19.6 degrees. If we set the vertical exaggeration in the upper left window to 1.0 (no exaggeration), this estimation looks reasonable.

- g. The deep valley on the southwestern side of the volcano, running roughly between $4^{\circ} 40' 24''$ (4.6733°) N, $125^{\circ} 5' 11''$ (125.0864°) E and $4^{\circ} 39' 38''$ (4.6606°) N, $125^{\circ} 4' 44''$ (125.0789°) E appears to have relatively steep topography and would be an interesting place to look for biological organisms.

Notes
