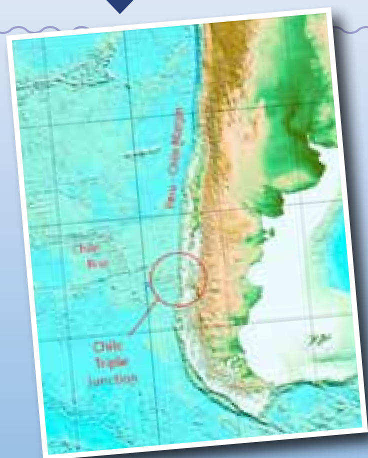


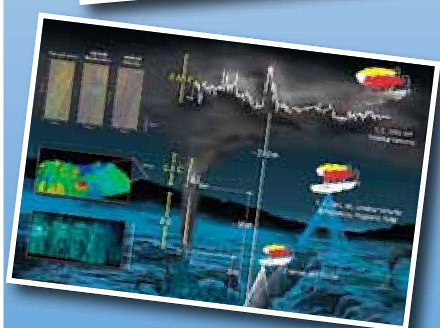


Image captions/credits on Page 2.

lesson plan

INSPIRE: Chile Margin 2010

The Ridge Exploring Robot

Focus
Autonomous Underwater Vehicles/Marine Navigation

Grade Level
9-12 (Earth Science/Mathematics)

Focus Question
How do ocean explorers use autonomous underwater robots to locate hydrothermal vents in the deep ocean?

Learning Objectives
- Students will explain a three-phase strategy that uses an autonomous underwater vehicle (AUV) to locate, map, and photograph previously undiscovered hydrothermal vents.
- Students will design a program for an AUV survey of a hydrothermal vent field on the Atlantic Mid-Ocean Ridge.
- Students will calculate the expected position of an AUV based on speed and direction of travel.

Materials
- Rulers or dividers for measuring distance
- Parallel rules or two drafting triangles for transferring course lines to a compass rose
- One copy of each of the following for each student or student group:
  - Yoerger *et al.*, 2007 (see Other Resources);
  - *Student Worksheet on Dead Reckoning and Navigation with Nautical Charts*;
  - *Autonomous Benthic Explorer Overview*

Audio-Visual Materials
- (Optional) video or computer projection equipment to show images from the INSPIRE: Chile Margin 2010 Web page (http://oceanexplorer.noaa.gov/explorations/10chile/welcome.html)

Teaching Time
Two 45-minute class periods, plus time for student assignments

Seating Arrangement
Groups of 3-4 students

Maximum Number of Students

32

Key Words

Autonomous underwater vehicle
Navigation
Hydrothermal vent
Autonomous Benthic Explorer (ABE)

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.

[On March 5, 2010, scientists participating in the INSPIRE: Chile Margin 2010 Expedition lost contact with the Autonomous Benthic Explorer (ABE) underwater robot during its 222nd dive. Despite numerous backup systems and procedures, ABE was not heard from again.]

Earthquakes and volcanoes are among Earth's most spectacular and terrifying geological events. The Mount St. Helens eruption of 1980 and the Haiti (7.0 magnitude) and Chile (8.8 magnitude) earthquakes of 2010 are recent and memorable examples of the extreme power that often accompanies these events. The Indian Ocean tsunami of 2004 was caused by an underwater earthquake that is estimated to have released the energy of 23,000 Hiroshima-type atomic bombs, and caused the deaths of more than 150,000 people.

Volcanoes and earthquakes are both linked to movements of tectonic plates, which are portions of the Earth's outer crust (the lithosphere) about 5 km thick, as well as the upper 60 - 75 km of the underlying mantle. These plates move on a hot flowing mantle layer called the asthenosphere, which is several hundred kilometers thick. Heat within the asthenosphere creates convection currents (similar to the currents that can be seen if food coloring is added to a heated container of water). Movement of convection currents causes tectonic plates to move several centimeters per year relative to each other.

Where tectonic plates slide horizontally past each other, the boundary between the plates is known as a transform plate boundary. As the plates rub against each other, huge stresses are set up that can cause portions of the rock to break, resulting in earthquakes. Places where these breaks occur are called faults. A well-known example of a transform plate boundary is the San Andreas fault in California. View animations of different types of plate boundaries at: http://www.seed.slb.com/flash/science/features/earth/livingplanet/plate_boundaries/en/index.html.

Images from Page 1 top to bottom:
Map of the Southeast Pacific Ocean and South American continent showing the Chile Rise spreading center, the Peru-Chile Margin, and the location of the Chile Triple Junction. *Photo credit: INSPIRE: Chile Margin 2010.*
http://oceanexplorer.noaa.gov/explorations/10chile/background/geology/media/geology1.html

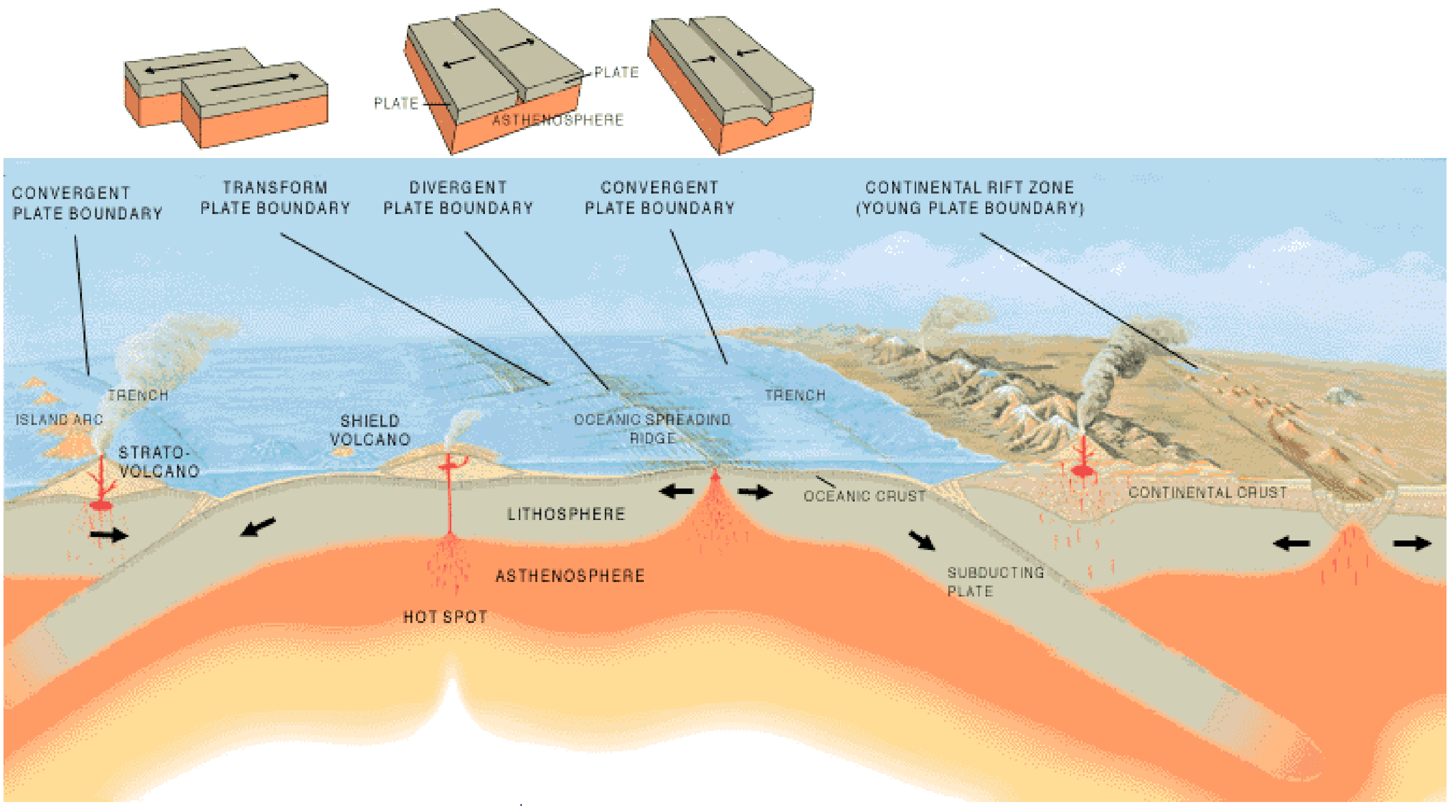
Our 3-phased approach to ocean exploration with ABE. First, guided by chemical measurements made aboard ship, we program ABE to fly around within the water column "sniffing" for where the chemical signals are strongest using specialized in situ sensors. Second, once we know where the strongest chemical signals from a hydrothermal vent are, we program ABE to fly closer to the seafloor, making detailed maps of the seabed and, ideally, also intercepting the stems of hot buoyant hydrothermal plumes of water rising up above the seafloor. Third, and finally, we program ABE up once more to descend to right above the seabed and drive to and fro, very carefully – using obstacle avoidance techniques to stop it from crashing into the rough rocky terrain it finds – while taking photographs of whatever it is we have found: hydrothermal vents, cold seeps, and whatever new and unique animals they might host. *Photo credit: Christopher German.*
http://oceanexplorer.noaa.gov/explorations/10chile/background/exploration/media/exploration2.html

The ABE (Autonomous Benthic Explorer) autonomous underwater vehicle (free-swimming robot) about to be set loose to explore the bottom of the SW Indian Ocean from aboard the Chinese research ship RV Da Yang Yi Hao in Spring 2007. Over the past 5 years, ABE has been used on multiple expeditions to find new hydrothermal vents in the deep ocean all over the world, from New Zealand to South Africa and from Brazil to Ecuador. *Photo credit: Christopher German.*
http://oceanexplorer.noaa.gov/explorations/10chile/background/plan/media/missionplan3.html

A methane hydrate mound on the seafloor; bubbles show that methane is continuously leaking out of features like this. If bottom waters warmed, this entire feature may be destabilized and leak methane at a higher rate. *Photo credit: INSPIRE: Chile Margin 2010.*
http://oceanexplorer.noaa.gov/explorations/10chile/background/methane/media/methane4.html

A convergent plate boundary is formed when tectonic plates collide more or less head-on. When two continental plates collide, they may cause rock to be thrust upward at the point of collision, resulting in mountain-building. (The Himalayas were formed by the collision of the Indo-Australian Plate with the Eurasian Plate). When an oceanic plate and a continental plate collide, the oceanic plate moves beneath the continental plate in a process known as subduction. Deep trenches are often formed where tectonic plates are being subducted, and earthquakes are common. As the sinking plate moves deeper into the mantle, fluids are released from the rock causing the overlying mantle to partially melt. The new magma (molten rock) rises and may erupt violently to form volcanoes, often forming arcs of islands along the convergent boundary. These island arcs are always landward of the neighboring trenches. View the 3-dimensional structure of a subduction zone at:
http://www.seed.slb.com/flash/science/features/earth/livingplanet/plate_boundaries/en/index.html.

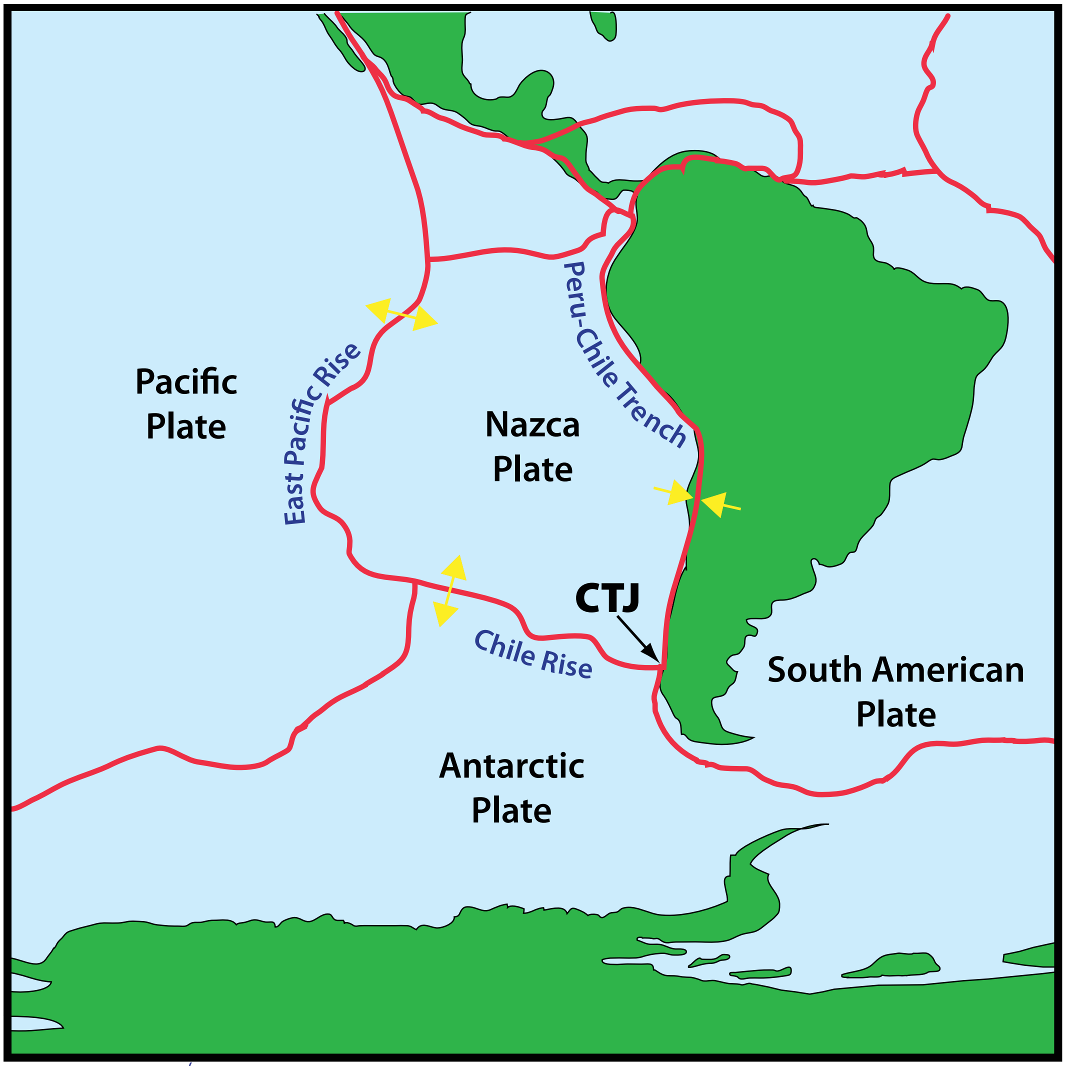
Figure 1: Types of Plate Boundaries



Artist's cross section illustrating the main types of plate boundaries. (*Cross section by José F. Vigil from This Dynamic Planet -- a wall map produced jointly by the U.S. Geological Survey, the Smithsonian Institution, and the U.S. Naval Research Laboratory.*)
http://pubs.usgs.gov/gip/dynamic/Vigil.html

Where tectonic plates are moving apart, they form a divergent plate boundary. At divergent plate boundaries, magma rises from deep within the Earth and erupts to form new crust on the lithosphere. Most divergent plate boundaries are underwater (Iceland is an exception), and form submarine mountain ranges called oceanic spreading ridges. While the process is volcanic, volcanoes and earthquakes along oceanic

Figure 2: Chile Triple Junction



spreading ridges are not as violent as they are at convergent plate boundaries. View the 3-dimensional structure of a mid-ocean ridge at: http://oceanexplorer.noaa.gov/explorations/03fire/logs/ridge.html.

Along the western coast of Chile, three of Earth's tectonic plates intersect in a way that does not occur anywhere else on the planet (see Figure 2). Chile, and the other countries of South America, lie on top of the South American tectonic plate. To the west of Chile, the Nazca Plate extends beneath the Pacific Ocean and meets the Pacific Plate along a divergent plate boundary called the East Pacific Rise. The southern edge of the Nazca Plate adjoins the Antarctic Plate along another divergent plate boundary called the Chile Rise. The eastern edge of the Chile Rise is being subducted beneath the South American plate at the Chile Triple Junction (CTJ), which is unique because it consists of a mid-oceanic ridge being subducted under a continental tectonic plate. The eastern portion of the Nazca Plate is also being subducted along the Peru-Chile Trench, and the Andes mountains are one consequence of this process. Not surprisingly, complex movements of three tectonic plates at the CTJ result in numerous earthquakes. In fact, the largest earthquake ever recorded (magnitude 9.5) occurred along the Peru-Chile Trench in 1960. While earthquakes and volcanoes are often associated with massive destruction and loss of human life, the same processes that cause these events are also responsible for producing unique habitats for very different life forms.

One of the most exciting and significant scientific discoveries in the history of ocean science was made in 1977 at a divergent plate boundary near the Galapagos Islands. Here, researchers found large numbers of animals that had never been seen before clustered around underwater hot springs flowing from cracks in the lava seafloor. Similar hot springs, known as hydrothermal vents, have since been found in many other locations where underwater volcanic processes are active. Hydrothermal vents are formed when the movement of tectonic plates causes deep cracks to form in the ocean floor. Seawater flows into these cracks, is heated by magma, and then rises back to the surface of the seafloor. The water does not boil because of the high pressure in the deep ocean, but may reach temperatures higher than 350° C. This superheated water dissolves minerals in Earth's crust. Hydrothermal vents are locations where the superheated water erupts through the seafloor. The temperature of the surrounding water is near-freezing, which causes some of the dissolved minerals to precipitate from the solution. This makes the hot water plume look like black smoke, and in some cases the precipitated minerals form chimneys or towers.

The presence of thriving biological communities in the deep ocean was a complete surprise, because it was assumed that food energy resources would be scarce in an environment without sunlight to support photosynthesis. Researchers soon discovered that the organisms responsible for this biological abundance do not need photosynthesis, but instead are able to obtain energy from chemical reactions through a process known as chemosynthesis. Photosynthesis and chemosynthesis both require a source of energy that is transferred through a series of chemical reactions into organic molecules that living organisms may use as food. In photosynthesis, light provides this energy. In chemosynthesis, the energy comes from other chemical reactions. Energy for chemosynthesis in the vicinity of hydrothermal vents often comes from hydrogen sulfide. Cold seeps are another type of chemosynthetic deep-sea community in which hydrocarbons (such as methane or oil) seeping out of sediments provide an energy source for living organisms. Cold seeps are commonly found along continental margins, and are home to many species that have not been found anywhere else on Earth.

Although 30 years have passed since the discovery of the first hydrothermal vents, more than 90% of the global ridge crest still has not been explored for the presence or absence of hydrothermal activity

(German *et al.*, 2008). A primary purpose of the INSPIRE: Chile Margin 2010 expedition is to locate new chemosynthetic ecosystems near the CTJ. Because hydrothermal vents and cold-seeps cause changes to the chemistry and physical characteristics of surrounding seawater, these geologic features are often surrounded by masses of seawater that are distinctly different from normal seawater. These water masses are called plumes, and provide ocean explorers with clues about the location of hydrothermal vents and cold-seeps.

To search for these clues, expedition scientists will use deep-tow sidescan sonar and data recorders that can detect chemical and physical water characteristics that signal the presence of hydrothermal vents and cold-seeps. Once plumes have been located, the depth and size of selected plumes will be investigated in more detail using instruments that measure conductivity, temperature, depth, optical backscatter, and redox potential so that the source of the plume can be located within an area of about 1 km. High resolution maps of this area will be prepared using an autonomous underwater vehicle (AUV). Finally, the AUV will collect overlapping photographs of the vent or cold-seep site. This lesson focuses on the AUV known as the Autonomous Benthic Explorer (ABE). For more information and activities about physical and chemical measurements and some of the technologies used to make these measurements, please see "The Oceanographic Yo-Yo" lesson. For more about ocean floor mapping, please see the "Mapping the Deep Ocean Floor" lesson. These lessons can be found in the lesson plan collection for INSPIRE: Chile Margin 2010 Expedition.

Learning Procedure

*[NOTE: Portions of this lesson are adapted from the National Ocean Service Discovery Classroom Lesson, "Plot Your Course" (*http://oceanservice.noaa.gov/education/classroom/lessons/18_marinenav_plotcourse.pdf)*]*

1. To prepare for this lesson:
   (a) Review introductory essays for the INSPIRE: Chile Margin 2010 Expedition at http://oceanexplorer.noaa.gov/explorations/10chile/welcome.html, and logs from March 7, 2010 that chronicle the loss of ABE (http://oceanexplorer.noaa.gov/explorations/10chile/logs/mar7/mar7.html and http://oceanexplorer.noaa.gov/explorations/10chile/logs/mar7a/mar7a.html)
   (b) Review the *Autonomous Benthic Explorer Overview*, and information about ABE at http://oceanexplorer.noaa.gov/technology/subs/abe/abe.html and http://dsg.whoi.edu:90/ships/auvs/abe_description.htm.
   (c) Review questions on the *Hydrothermal Vent Exploration with ABE Student Guide*, referenced Web pages, and Yoerger *et al*. 2007. In

addition to introducing students to the ABE robot, the *Student Guide* is also intended to lead students to the Ocean Explorer Web site, which contains video clips, photographic imagery, interviews, essays, daily logs, and other information about a wide variety of expeditions to explore Earth's ocean. High school students may not be familiar with all of the technical terms contained in the Yoerger *et al.* paper, but these terms are not needed to address *Student Guide* questions, and an internet search will quickly provide explanations of most terms used in the paper.

(d) Review the *Student Worksheet on Dead Reckoning and Navigation with Nautical Charts*, work through the dead reckoning calculations, and gather materials that student groups will need to complete this activity.

(e) You may also want to review http://oceanexplorer.noaa.gov/explorations/02fire/logs/magicmountain/welcome.html, which links to simulated fly-throughs of the Magic Mountain hydrothermal vent site; and http://oceanexplorer.noaa.gov/explorations/02fire/logs/leg1_sum/media/linked.html, which is an animated video that shows the deployment of ABE, and the different sonar surveys that were used to characterize the Magic Mountain site.

2. Introduce the mission of the INSPIRE: Chile Margin 2010 Expedition, and discuss how expedition scientists prospect for undiscovered hydrothermal vents and cold seeps. You may want to briefly describe multibeam mapping and physical/chemical sensor arrays discussed in "The Oceanographic Yo-Yo" and "Mapping the Deep Ocean Floor" lessons included in the lesson plan collection for this expedition. Be sure students understand that the essence of their approach is to use different technologies to detect evidence of these features, beginning with sidescan sonar and towed sensors over large areas of the ocean floor. When chemical and/or physical clues are detected that signal the presence of vents or seeps, the search shifts to a three-phase strategy using the ABE robot.

   In Phase 1, ABE is programmed to cruise in a zig-zag pattern over an area of about 5 km x 5 km, several hundred meters above the ocean floor while sensors carried aboard the robot locate the strongest chemical and physical traces of vents or seeps. The individual legs of the zig-zag pattern are about 500 m apart in this first stage. In Phase 2, ABE is programmed to obtain high resolution maps areas where traces are strongest, covering an area of about 1 km x 1 km from about 50 m above the ocean floor. The zig-zag legs are about 30 m apart in this stage. The robot continues to collect chemical and physical data that will further pinpoint the location of seawater altered by seeps or vents. For Phase 3, ABE is programmed to cover an area of 200 m x 200 m around individual vent or seep sites and obtain a series of photographs from a distance of about 5 m above the bottom with about 5 m between zig-zag legs so that overlapping images are produced that can be assembled into photo-mosaics of each site.

Figure 3: CTJ's 3-phased approach to ocean exploration with ABE.

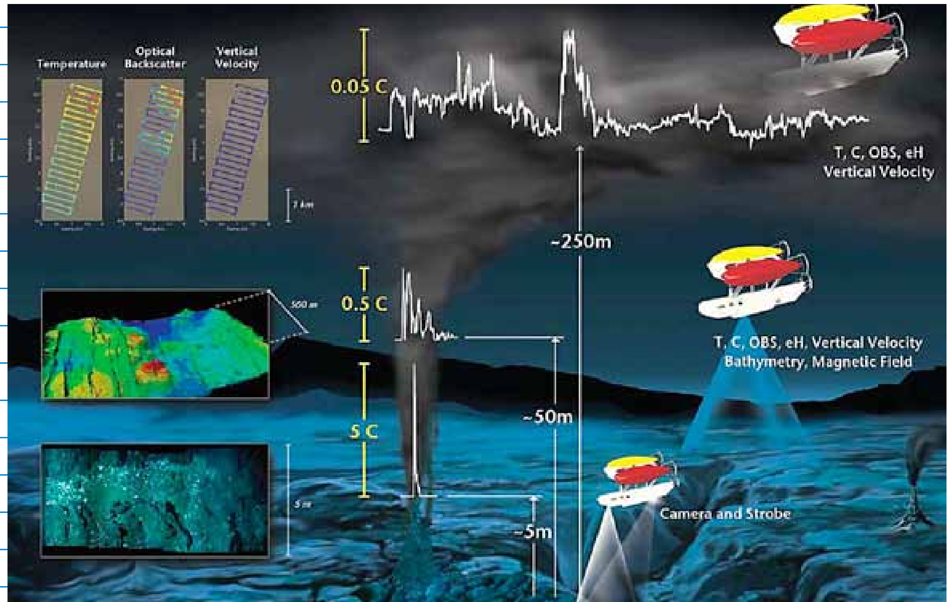


Illustration courtesy of Christopher German, INSPIRE: Chile Margin 2010 Expedtion.
http://oceanexplorer.noaa.gov/explorations/10chile/background/exploration/media/exploration2.html

Briefly discuss the loss of ABE on March 6, 2010. This event highlights the fact that exploration is often a risky proposition, and underscores one of the major advantages of underwater robots: reducing threats to the lives of human explorers.

3. Provide each student group with copies of *Autonomous Underwater Vehicles Overview* and *Hydrothermal Vent Exploration with ABE Student Guide*. Be sure students understand that Yoerger *et al.* use different names for expeditions referenced on the *Worksheet*: the Galapagos Rift 2002 Expedition, Submarine Ring of Fire 2002 Expedition, and New Zealand American Submarine Ring of Fire 2007 Expedition are referred to as Galapagos 2002, Explorer Ridge 2002, and Kermadec Arc, respectively.

4. Discuss students' answers to *Worksheet* questions. This discussion should include:
   - During the Galapagos Rift 2002 Expedition explorers discovered that the Rose Garden site appeared to have been covered by lava from a recent underwater volcanic eruption.
   - The Galapagos Rift 2002 Expedition also used the manned submersible *Alvin*, and safety concerns prohibited simultaneous use of ABE.
   - Temperature differences detected during the Galapagos Rift 2002

Expedition were on the order of 50 millidegrees (0.05 degree). While such differences seem small, they are significant because the temperature of the surrounding water is extremely uniform.
- During the Galapagos Rift 2002 Expedition, ABE carried sensors to measure conductivity and temperature. Scientists decided that an additional sensor to measure redox potential was needed.
- Multibeam sonar and sensors to measure redox potential and optical backscatter were added to ABE for the Submarine Ring of Fire 2002 (Explorer Ridge) Expedition.
- The primary mission for ABE during the New Zealand American Submarine Ring of Fire 2007 (Kermadec Arc) Expedition was fine-scale mapping of Brothers volcano.
- During the New Zealand American Submarine Ring of Fire 2007 (Kermadec Arc) Expedition, ABE's ability to "park" itself allowed the robot to operate independently of the surface ship for long periods of time.
- Temperature, redox potential, and optical backscatter sensors carried aboard ABE during the New Zealand American Submarine Ring of Fire 2007 (Kermadec Arc) Expedition were particularly useful for locating hydrothermal activity.

5. Provide each student group with copies of *Student Worksheet on Dead Reckoning and Navigation with Nautical Charts*, and work through the example with the entire class to ensure that the basic concepts are understood. Be sure students distinguish between dead reckoning positions, which are estimates of the true geographic position, and fixes which are more accurate (but still subject to errors) position estimates. You may also want to remind students that velocity is a vector quantity that includes direction as well as speed.

   Tell students that their assignment is to design a Phase 1 survey program for ABE to prospect for hydrothermal vents along a portion of the Mid-Atlantic Ridge described in Yoerger *et al.*, 2007. To do this, they will use dead reckoning techniques to calculate appropriate speed and course instructions that would allow the robot to cover the area illustrated in Figure 6 of the worksheet.

6. Evaluate and discuss students' results. The completely plotted track is illustrated in Figure 7. The instructions for the entire survey are:

   1. Begin at 4°49.9'S, 12°21.1'W
   2. Run on Course = 254° for 1.75 hr
   3. Run on Course = 344° for 0.417 hr
   4. Run on Course = 074° for 1.75 hr
   5. Run on Course = 344° for 0.417 hr
   6. Run on Course = 254° for 2.083 hr
   7. Run on Course = 344° for 0.417 hr

8. Run on Course = 074° for 2.083 hr
9. Run on Course = 344° for 0.417 hr
10. Run on Course = 254° for 2.083 hr
11. Run on Course = 344° for 0.417 hr
12. Run on Course = 074° for 2.083 hr

If time permits, you may want to have student groups try to plot the course instructions from another student group to see how well these instructions produce the desired survey track. You may also want to discuss other navigation techniques that can be used to establish an AUV's geographic position.

The BRIDGE Connection

www.vims.edu/bridge/ – Click on "Ocean Science Topics" in the menu on the left side of the page, then "Human Activities," then "Technology" for links to resources about submersibles, ROVs, and other technologies used in underwater exploration.

The "Me" Connection

Many stories have been written about robots that have or acquire human characteristics (one of the most famous is "Data" from the television series Star Trek: The Next Generation). Have students read the INSPIRE: Chile Margin 2010 Expedition daily logs for March 7, 2010, then write a brief essay describing how they think scientists felt about losing their mechanical colleague, and how they would personally feel under similar circumstances.

Connections to Other Subjects

English/Language Arts, Earth Science

Assessment

Written reports and class discussions provide opportunities for assessment.

Extensions

1. Visit http://oceanexplorer.noaa.gov/explorations/10chile/welcome.html for the latest activities and discoveries by the INSPIRE: Chile Margin 2010 Expedition.
2. Visit http://www.marinetech.org/rov_competition/rov_video_2007.php for a video from the the Marine Technology Society's student ROV competition, and links to other sites about underwater robots.
3. For ideas about building your own underwater robots, see Bohm, H. and V. Jensen. 1998. Build Your Own Programmable Lego Submersible: Project: Sea Angel AUV (Autonomous Underwater Vehicle). Westcoast Words. 39 pages; and Bohm, H. 1997. Build your own underwater robot and other wet projects. Westcoast Words. 148 pages.

Other Relevant Lesson Plans from NOAA's Ocean Exploration Program

My Wet Robot
(PDF, 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 (Physical Science)

Students will be able to 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.

Sound Pictures
(PDF, 1 Mb) (from the *Lophelia* II 2009: Deepwater Coral Expedition: Reefs, Rigs, and Wrecks)
http://oceanexplorer.noaa.gov/explorations/09lophelia/welcome.html

Focus: Sonar (Physical Science)

In this activity, students will explain the concept of sonar, describe the major components of a sonar system, explain how multibeam and sidescan sonar systems are useful to ocean explorers, and simulate sonar operation using a motion detector and a graphing calculator.

Chemosynthesis for the Classroom
(PDF, 274 kb) (from the 2002 Gulf of Mexico Expedition)
http://oceanexplorer.noaa.gov/explorations/02mexico/background/edu/media/gom_chemo_gr912.pdf

Focus: Chemosynthetic bacteria and succession in chemosynthetic communities (Chemistry/Biology)

Students will observe the development of chemosynthetic bacterial communities and will recognize that organisms modify their environment in ways that create opportunities for other organisms to thrive. Students will also be able to explain the process of chemosynthesis and the relevance of chemosynthesis to biological communities in the vicinity of cold seeps.

Hydrothermal Vent Challenge
(PDF, 412 kb) (from the Submarine Ring of Fire 2004 Expedition)
http://oceanexplorer.noaa.gov/explorations/04fire/background/edu/media/RoF.ventchall.pdf

Focus: Chemistry of hydrothermal vents (Chemistry)

Students will be able to define hydrothermal vents and explain the overall processes that lead to their formation. Students will be able to explain the origin of mineral-rich fluids associated with hydrothermal vents. Students will be able to explain how black smokers and white smokers are formed. Students will be able to hypothesize how properties of hydrothermal fluids might be used to locate undiscovered hydrothermal vents.

Lost City Chemistry Detectives
(PDF, 326 kb) (from the Lost City 2005 Expedition)
http://oceanexplorer.noaa.gov/explorations/05lostcity/background/edu/media/lostcity05_chemdetect.pdf

Focus: Chemistry of the Lost City Hydrothermal Field (Chemistry/Earth Science)

Students will be able to compare and contrast the formation processes that produce black smokers and the Lost City hydrothermal field, describe the process of serpentinization and how this process contributes to formation of chimneys at the Lost City hydrothermal field, and describe and explain the chemical reactions that produce hydrogen and methane in Lost City hydrothermal vent fluids.

Massif Mystery
(PDF, 327 kb) (from the Lost City 2005 Expedition)
http://oceanexplorer.noaa.gov/explorations/05lostcity/background/edu/media/lostcity05_massif.pdf

Focus: (Earth Science) Structure and Origin of the Atlantis Massif

Students will be able to compare and contrast basalt, gabbro, and peridotite; explain what the presence of these rocks may suggest about the origin of formations where they are found; and describe and interpret research data that suggest possible origins of the Atlantis Massif.

Where There's Smoke, There's...
(PDF, 248 kb) (from the New Zealand American Submarine Ring of Fire 2005 Expedition)
http://oceanexplorer.noaa.gov/explorations/05fire/background/edu/media/rof05_smoke.pdf
Focus: Hydrothermal vent chemistry at subduction volcanoes (Chemistry)

Students will be able to use fundamental relationships between melting points, boiling points, solubility, temperature, and pressure to develop plausible explanations for observed chemical phenomena in the vicinity of subduction volcanoes.

Where's My 'Bot?
(PDF, 492 kb) (from the Bonaire 2008: Exploring Coral Reef Sustainability with New Technologies Expedition)
http://oceanexplorer.noaa.gov/explorations/08bonaire/background/edu/media/wheresbot.pdf

Focus: Marine Navigation (Earth Science/Mathematics)

In this activity, students will estimate geographic position based on speed and direction of travel, and integrate these calculations with GPS data to estimate the set and drift of currents.

Thar She Blows!
(PDF, 456 kb) (from the 2002 Galapagos Rift Expedition)
http://oceanexplorer.noaa.gov/explorations/02galapagos/background/education/media/gal_gr9_12_l3.pdf

Focus: Hydrothermal vents

In this activity, students will demonstrate an understanding of how the processes that result in the formation of hydrothermal vents create new ocean floor; students will demonstrate an understanding of how the transfer of energy effects solids and liquids.

The Big Burp: Where's the Proof?
(PDF, 364 kb) (from the Expedition to the Deep Slope 2007 Expedition)
http://oceanexplorer.noaa.gov/explorations/07mexico/background/edu/media/burp.pdf

Focus: Potential role of methane hydrates in global warming (Earth Science)

In this activity, students will be able to describe the overall events that occurred during the Cambrian explosion and Paleocene extinction events and will be able to define methane hydrates and hypothesize how these substances could contribute to global warming. Students will also be able to describe and explain evidence to support the hypothesis that methane hydrates contributed to the Cambrian explosion and Paleocene extinction events.

The Census of Marine Life
(PDF, 300 kb) (from the 2007: Exploring the Inner Space of the Celebes Sea Expedition]
http://oceanexplorer.noaa.gov/explorations/07philippines/background/edu/media/census.pdf

Focus: The Census of Marine Life (Biology)

In this activity, students will be able to describe the Census of Marine Life (CoML) and explain in general terms the CoML strategy for assessing and explaining the changing diversity, distribution and abundance of marine species from the past to the present, and for projecting the future of marine life. Students will also be able to use the Ocean Biogeographic Information System to retrieve information about ocean species from specific geographic areas.

The Galapagos Spreading Center
(PDF, 480 kb) (from the 2002 Galapagos Rift Expedition)
http://oceanexplorer.noaa.gov/explorations/02galapagos/background/education/media/gal_gr9_12_l2.pdf

Focus: Mid-Ocean Ridges (Earth Science)

Students will be able to describe the processes involved in creating new seafloor at a mid-ocean ridge; students will investigate the Galapagos Spreading Center system; students will understand the different types of plate motion associated with ridge segments and transform faults.

The Roving Robotic Chemist
(PDF, 440 kb) (from the PHAEDRA 2006 Expedition)
http://oceanexplorer.noaa.gov/explorations/06greece/background/edu/media/robot_chemist.pdf

Focus: Mass Spectrometry (Physical Science)

In this lesson, students will be able to explain the basic principles underlying mass spectrometry, discuss the advantages of in-situ mass spectrometry, explain the concept of dynamic re-tasking as it applies to an autonomous underwater vehicle, and develop and justify a sampling strategy that could be incorporated into a program to guide an AUV searching for chemical clues to specific geologic features.

This Life Stinks
(PDF, 276 kb) (from the 2003 Windows to the Deep Expedition)
http://oceanexplorer.noaa.gov/explorations/03windows/background/education/media/03win_lifestinks.pdf

Focus: Methane-based chemosynthetic processes (Physical Science)

Students will be able to define the process of chemosynthesis, and contrast this process with photosynthesis. Students will also explain the process of methane-based chemosynthesis and explain the relevance of chemosynthesis to biological communities in the vicinity of cold seeps.

This Old Tubeworm
(PDF, 484 kb) (from the 2002 Gulf of Mexico Expedition)
http://oceanexplorer.noaa.gov/explorations/02mexico/background/edu/media/gom_oldtube.pdf

Focus: Growth rate and age of species in cold-seep communities

Students will be able to explain the process of chemosynthesis, explain the relevance of chemosynthesis to biological communities in the vicinity of cold seeps, and construct a graphic interpretation of age-specific growth, given data on incremental growth rates of different-sized individuals of the same species. Students will also be able to estimate the age of an individual of a specific size, given information on age-specific growth in individuals of the same species.

Where Did They Come From?
(PDF, 296 kb) (from the 2005 GalAPAGoS: Where Ridge Meets Hotspot Expedition)
http://oceanexplorer.noaa.gov/explorations/05galapagos/background/edu/media/05galapagos_biogeography.pdf

Focus: Species variation in hydrothermal vent communities (Life Science)

Students will define and describe biogeographic provinces of hydrothermal vent communities, identify and discuss processes contributing to isolation and species exchange between hydrothermal vent communities, and discuss characteristics which may contribute to the survival of species inhabiting hydrothermal vent communities.

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/10chile/welcome.html – Web site for the INSPIRE: Chile Margin 2010 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

Yoerger, D., A. Bradley, M. Jakuba, M. Tivey, C. German, T. Shank, R. Embley. 2007. Mid-ocean ridge exploration with an autonomous underwater vehicle. Oceanography 20(4):52-61(available online at http://www.tos.org/oceanography/issues/issue_archive/issue_pdfs/20_4/20.4_yoerger_et_al.pdf)

German, C., D. Yoerger, M. Jakuba, T. Shank, C. Langmuir, K. Nakamura. 2008. Hydrothermal exploration with the Autonomous Benthic Explorer. Deep-Sea Research I 55:203-219

Bohm, H. and V. Jensen. 1998. Build Your Own Programmable Lego Submersible: Project: Sea Angel AUV (Autonomous Underwater Vehicle). Westcoast Words. 39 pages.

Bohm, H. 1997. Build your own underwater robot and other wet projects. Westcoast Words. 148 pages.

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
- Motions and forces

Content Standard C: Life Science
- Populations and ecosystems
- Diversity and adaptations of organisms

Content Standard D: Earth and Space Science
- Energy in the Earth system
- Geochemical cycles

Content Standard E: Science and Technology
- Abilities of technological design
- Understandings about science and technology

Content Standard F: Science in Personal and Social Perspectives
- Natural and human-induced hazards
- Science and technology in local, national, and global challenges

Content Standard G: History and Nature of Science
- Science as a human endeavor

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 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.

Essential Principle 5.
The ocean supports a great diversity of life and ecosystems.

Fundamental Concept e. Tectonic activity, sea level changes, and force of waves influence the physical structure and landforms of the coast.
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.
Fundamental Concept g. There are deep ocean ecosystems that are independent of energy from sunlight and photosynthetic organisms. Hydrothermal vents, submarine hot springs, and methane cold seeps rely only on chemical energy and chemosynthetic organisms to support life.

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

We value your feedback on this lesson.
Please send your comments to:
oceanexeducation@noaa.gov

For More Information

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The Ridge Exploring Robot

Autonomous Underwater Vehicles Overview

Autonomous Underwater Vehicles (AUVs) are underwater robots that operate without a pilot or cable to a ship or submersible. This independence allows AUVs to cover large areas of the ocean floor, as well as to monitor a specific underwater area over a long period of time. Typical AUVs can follow the contours of underwater mountain ranges, fly around sheer pinnacles, dive into narrow trenches, take photographs, and collect data and samples.

Until recently, once an AUV was launched it was completely isolated from its human operators until it returned from its mission. Because there was no effective means for communicating with a submerged AUV, everything depended upon instructions programmed into the AUV's onboard computer. Today, it is possible for AUV operators to send instructions and receive data with acoustic communication systems that use sound waves with frequencies ranging roughly between 50 hz and 50 khz. These systems allow greater interaction between AUVs and their operators, but basic functions are still controlled by the computer and software onboard the AUV.

Key systems found on most AUVs include: propulsion, usually propellers or thrusters (water jets); power source such as batteries or fuel cells; environmental sensors such as video and devices for measuring water chemistry; computers to control the robot's movement and data gathering functions; and a navigation system.

The Autonomous Benthic Explorer (ABE) was designed to investigate the deep ocean floor to depths of 4,500 m. ABE consists of three pods connected by an open framework. Two upper pods contain glass balls that provide flotation, and the lower pods contains batteries that power thrusters and electronics. Five thrusters are mounted inside the framework between the three pods. Three thrusters provide lateral (horizontal movement) and two provide vertical motion. ABE is 3 m long, weighs 550 kg, and has a cruising speed of 0.6 m/sec (about 1.19 kn). Maximum operating range is 20 – 40 km or 14 – 20 hr, depending upon whether instruments are used that require large amounts of power (such as multibeam or photographic imaging systems).

Navigation has been one of the biggest challenges for AUV engineers. Today, everyone from backpackers to ocean freighters use global positioning systems (GPS) to find their location on Earth's surface. But GPS signals do not penetrate into the ocean (for more about GPS, visit http://oceanservice.noaa.gov/topics/navops/positioning/welcome.html). One way to overcome this problem is to estimate an AUV's position from its compass course, speed through the water, and depth. This method of navigation is called "dead reckoning," and was used for centuries before GPS was available. Dead reckoning positions are only estimates however, and are subject to a variety of errors that can become serious over long distances and extended time periods.

If an AUV is operating in a confined area, its position can be determined using acoustic transmitters that are set around the perimeter of the operating area. These transmitters may be moored to the seafloor, or installed in buoys. Some buoy systems also include GPS receivers, so the buoys' positions are constantly updated. Signals from at least three appropriately positioned transmitters can be used to accurately calculate the AUV's position. Although this approach can be very accurate, AUV operators must install the transmitters, and the AUV must remain within a rather small area.

A more sophisticated approach uses Inertial Navigation Systems (INS) that measure the AUV's acceleration in all directions. These systems provide highly accurate position estimates, but require periodic position data from another source for greatest accuracy. On surface vessels and aircraft equipped with INS, additional position data are often obtained from GPS. On underwater vessels, the accuracy of INS position estimates is greatly improved by using a Doppler Velocity Logger (DVL) to measure velocity of the vessel's speed. On some AUVs, several of these systems are combined to improve the overall accuracy of onboard navigation. ABE uses acoustic transmitters as well as a DVL. For more information about INS and DVL systems, visit http://www.oceanexplorer.noaa.gov/explorations/08auvfest.

The Ridge Exploring Robot

Hydrothermal Vent Exploration with ABE Student Guide

Use the following references to answer the questions below:

- Yoerger, D., A. Bradley, M. Jakuba, M. Tivey, C. German, T. Shank, R. Embley. 2007. Mid-ocean ridge exploration with an autonomous underwater vehicle. Oceanography 20(4):52-61(available online at http://www.tos.org/oceanography/issues/issue_archive/issue_pdfs/20_4/20.4_yoerger_et_al.pdf)

- Web site for the Galapagos Rift 2002 Expedition: http://oceanexplorer.noaa.gov/explorations/02galapagos/galapagos.html

- Web site for the Submarine Ring of Fire 2002 Expedition: http://oceanexplorer.noaa.gov/explorations/02fire/welcome.html

- Web site for the New Zealand American Submarine Ring of Fire 2007 Expedition: http://oceanexplorer.noaa.gov/explorations/07fire/welcome.html

1. One of the objectives of the Galapagos Rift 2002 Expedition was to re-visit the hydrothermal vent site called Rose Garden, which was discovered in 1979 and intensively studied in 1985, 1988, and 1990. What did the Expedition find?

2. What other exploration activity limited the use of ABE during the Galapagos Rift 2002 Expedition?

3. During the Galapagos Rift 2002 Expedition, ABE detected "temperature anomalies" that were associated with hydrothermal vents. How different were these temperatures from the temperature of the surrounding seawater?

4. What sensors were carried aboard ABE during the Galapagos Rift 2002 Expedition to measure physical and chemical conditions? What additional sensor did scientists decide they needed?

5. What new capabilities were added to ABE for the Submarine Ring of Fire 2002 (Explorer Ridge) Expedition that greatly enhanced information gathered about hydrothermal vent fields?

6. What was the primary mission for ABE during the New Zealand American Submarine Ring of Fire 2007 (Kermadec Arc) Expedition?

7. What new capability allowed ABE to operate independently of the surface ship for long periods during the New Zealand American Submarine Ring of Fire 2007 (Kermadec Arc) Expedition?

8. What sensors carried aboard ABE were particularly useful for locating hydrothermal activity during the New Zealand American Submarine Ring of Fire 2007 (Kermadec Arc) Expedition?

The Ridge Exploring Robot

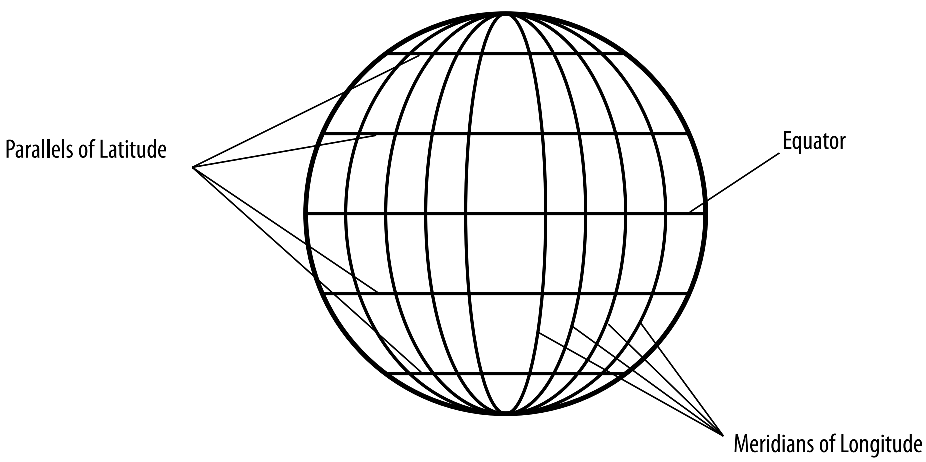
Student Worksheet on Dead Reckoning and Navigation with Nautical Charts

(adapted, in part, from the National Ocean Service Discovery Classroom Lesson, "Plot Your Course"; http://oceanservice.noaa.gov/education/classroom/lessons/18_marinenav_plotcourse.pdf)

Latitude and Longitude

All nautical charts are based on a system of geographic coordinates that can be used to describe a specific location on a body of water. One of the best-known and most widely used set of geographic coordinates is the latitude - longitude system. This system is based on two sets of imaginary circles on the Earth's surface. One set includes circles that pass through the north and south poles. These circles are known as "meridians of longitude." The other set includes circles that would lie on plane surfaces cutting through the Earth perpendicular to the polar axis (and therefore perpendicular to meridians of longitude). This second set of circles is known as "parallels of latitude" (see Figure 1).

Figure 1



Geographic coordinates using the latitude - longitude system are measured in terms of degrees. The reference point for all measurements of longitude is the meridian passing through Greenwich, England; this meridian is called the "prime meridian," and is represented by 0 degrees. The meridian of longitude that passes through any position on Earth is described in terms of how many degrees that meridian is to the east or west of the prime meridian. The maximum in either direction is 180 degrees. Parallels of latitude are measured in terms of how many degrees a given parallel is north or south from the equator (which is assigned a latitude of 0 degrees). Fractions of degrees are expressed in minutes (there are 60 minutes in one degree) and seconds (there are 60 seconds in one minute). Minutes and seconds are sometimes divided decimally for very precise descriptions of geographic location. Each degree of latitude corresponds to sixty nautical miles, so one minute of latitude corresponds to one nautical mile (a nautical mile is equal to about 6,076 ft, or about 1.15 statute miles).

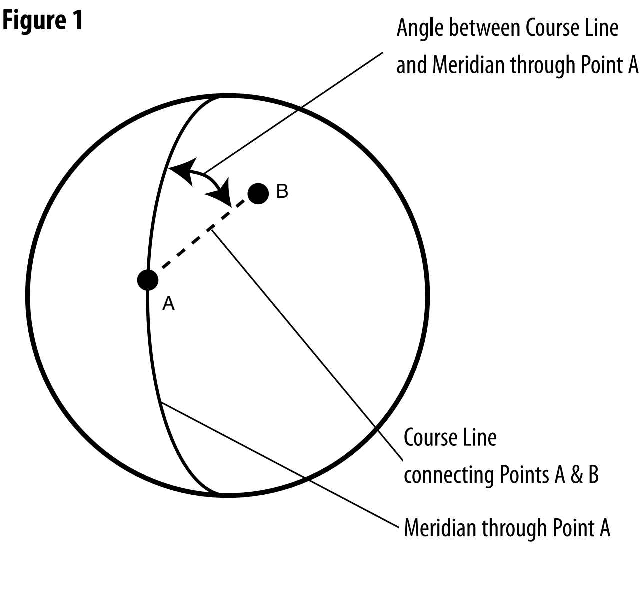
Useful Features of the Mercator Projection

A fundamental problem faced by all mapmakers is how to depict the three-dimensional curved surface of Earth on the two-dimensional flat surface of a paper chart. To deal with this problem, mapmakers use mathematical constructions known as "projection systems" to approximate Earth's curved surface in two dimensions. One of the most familiar projection systems is the Mercator projection, which is often explained as projection of Earth's surface features onto a cylinder wrapped so that the long axis of the cylinder is parallel to Earth's polar axis and the inner surface of the cylinder touches Earth's equator. A conspicuous feature of the Mercator projection is that meridians of longitude appear as straight vertical lines, and do not converge at the poles. The main advantage of charts that use the Mercator projection is that the geographic position of an object on the chart can be easily measured using the latitude and longitude scales along the four outer borders of the chart. A straight line drawn between two points on a Mercator chart corresponds to the compass direction between these points, and to the course that should be steered to navigate from one point to the other. In addition, the distance between the two points can be easily determined by transferring the length of a line between these points to the latitude scale on the left or right sides of the chart (most often using a pair of dividers), since one minute of latitude corresponds to one nautical mile as described above.

The Compass Rose

The compass rose is a tool provided on all nautical charts to simplify the process of measuring directions. The most commonly used reference point for direction on nautical charts is Earth's geographic north pole ("true north"). The direction from one point on Earth's surface to another point on Earth's surface is usually described as the angle between a line connecting the two points and the meridian that passes through the first point. It may be easier to visualize this angle as the compass course that one would follow to move from one point to the next if the compass pointed toward true north (see Figure 2).

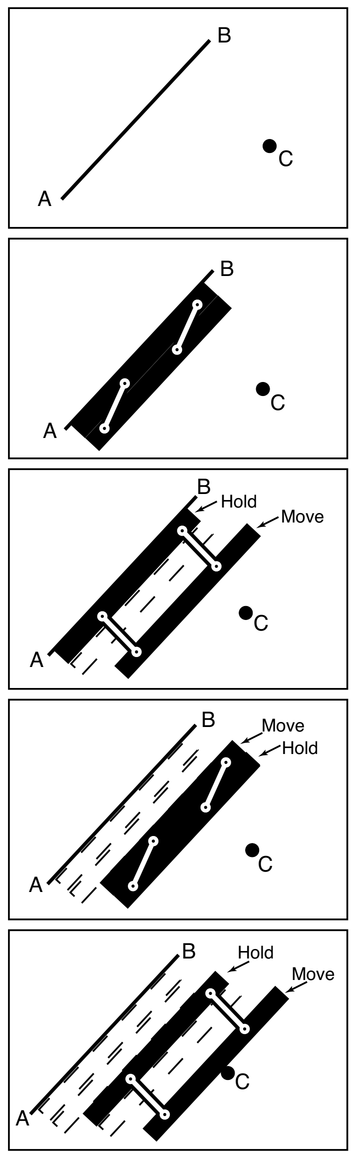
Figure 1



This angle is measured in degrees moving clockwise from the meridian. A compass rose on most charts consists of two or three concentric circles, several inches in diameter. Each circle is subdivided into smaller segments. The outer circle is divided into 360 segments (degrees) with zero at true north, usually indicated by a star. The next inner circle describes magnetic direction, also in degrees, with an arrow at the zero point which corresponds to the direction of magnetic north. The innermost circle (if there is one) is also oriented to magnetic north, but is divided into "points." This is a traditional way to express nautical directions based on subdividing the intervals between the four "cardinal" directions (north, east, south, and west). There are 32 points on the traditional mariner's compass (in this system, the points between north and east are named north, north by east, north-northeast, northeast by north, northeast, northeast by east, east-northeast, and east by north), and each point may be further divided into half- and quarter-points. This system is rarely used, except that north, northeast, east, southeast, etc. are sometimes used to give rough descriptions of direction, particularly wind direction.

To use a compass rose to determine direction (or "bearing") between two points, draw a line from the origin point to the destination point, then transfer the angle of this line to the nearest compass rose on the chart using parallel rulers or a pair of drafting triangles. Parallel rulers are two rulers connected by linkages that keep their edges parallel. To measure direction, line up the edge of one ruler with origin and destination points (or the bearing line), then "walk" the rulers (see Figure 3) to the nearest compass rose by alternately holding one ruler and moving the other until the edge of one ruler intersects the center point of the compass rose. Read the true direction on the scale of the outermost circle of the compass rose. To use a pair of drafting triangles, place the hypotenuses of the triangles together, then line up one of the other sides with the origin and destination points (or the bearing line). Holding one triangle in place, slide the other along the hypotenuse to the nearest compass rose, and read the direction as described above.

Figure 3



1. The Problem: How to transfer the angle of Line AB to Point C.
2. Align one edge of the parallel rules with Line AB.
3. Hold the rule next to Line AB, and "walk" the other rule toward Point C.
4. Hold the rule that was "walked," and move the other rule in the direction of Point C.
5. Continue "walking" the rules until Point C is reached. You can now draw a line through Point C that is parallel to Line AB.

Example of Dead Reckoning

Dead reckoning is the process of determining the geographic position of a vessel using the vessel's speed and course through the water. Because this position can be affected by many factors, it is only an estimate of a vessel's actual position, and is corrected from time to time by obtaining additional information that establishes a more accurate geographic position called a “fix” (such as information from a global positioning system or GPS). Often, a dead reckoning position is calculated using a nautical chart. Figure 4 shows an example of dead reckoning based on the following:

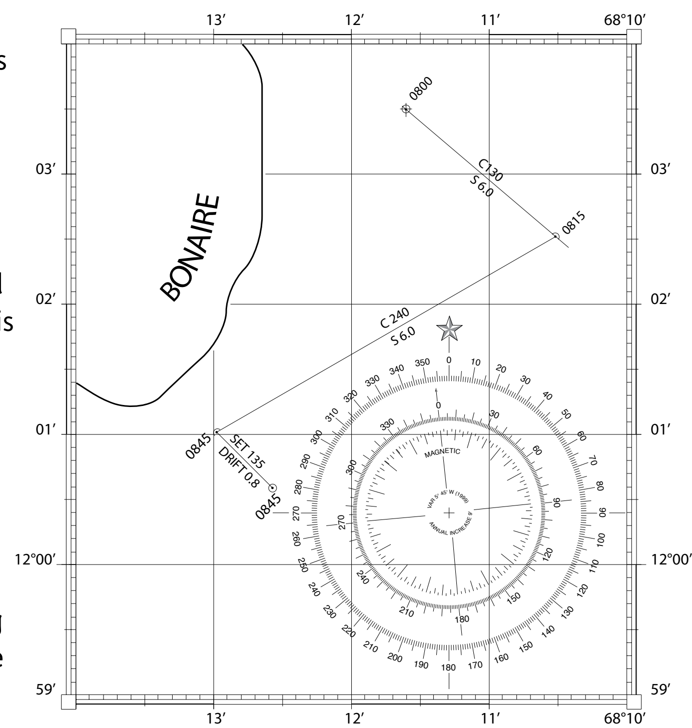


Figure 4. Example of Dead Reckoning

1. At 0800 the vessel obtains a GPS fix that establishes its geographic position as 12 degrees, 3.5 minutes north latitude, 68 degrees, 11.6 minutes west longitude (usually written as 12°03.5′N, 68°11.6′W). This position is plotted on the chart using the latitude (left and right sides) and longitude (top and bottom sides) scales. The position is indicated by a small circle with the time of the fix written nearby.

2. The vessel steers a course of 130° true (written 130T) with a speed of six knots (6 kn) for 15 minutes. A line is drawn from the starting point in the direction of 130T using parallel rules and the compass rose as described in Figure 3. The line is labeled with the course steered (beginning with a “C”) written on top of the line and the speed in knots (beginning with an “S”) written beneath the line. Since all courses and directions are plotted as true directions, it isn’t necessary to include a “T” after the number of degrees.

3. Since one knot is equal to one nautical mile per hour, a speed of 6 kn is equal to 6 nautical miles per hour, so in 15 minutes the vessel travelled

   $$(15 \text{ min} \div 60 \text{ min/hr}) \cdot (6 \text{ nm/hr}) = 1.5 \text{ nm}$$

   Since one minute of latitude is equal to one nautical mile, you can use the latitude scale on the left or right side of the chart to find the length of a line equivalent to 1.5 nm. Using a ruler or pair of dividers, this length is transferred to the course line drawn in Step 2. The end of this line represents a dead reckoning position at 0815. Notice that dead reckoning positions are marked with a semicircle and the time.

4. At 0815, the vessel changes course to 240T, and continues for 30 minutes at the same speed (6 kn). To plot this information, a line is drawn from the 0815 position in the direction of 240T, and a length equal to the distance travelled in 30 minutes is measured on the latitude scale

   $$(30 \text{ min} \div 60 \text{ min/hr}) \cdot (6 \text{ nm/hr}) = 3 \text{ nm which is equivalent to three minutes of latitude.}$$

Again, the dead reckoning position at 0845 is marked on the chart with a semicircle.

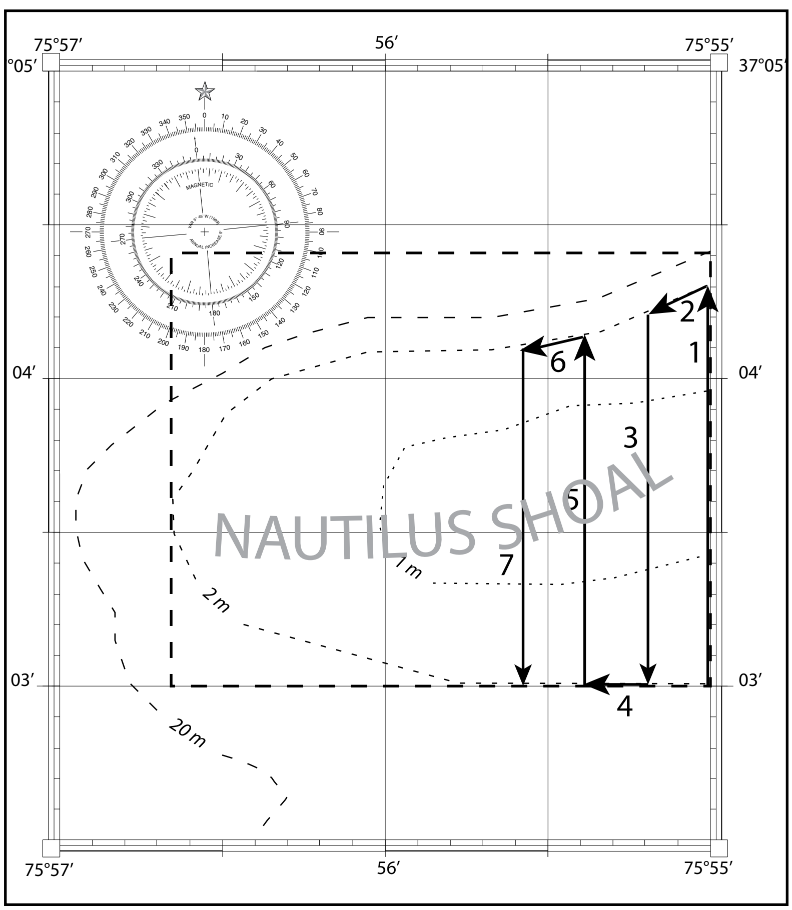
5. At 0845, the vessel obtains a GPS fix that establishes its true geographic position as 12°00.65'N, 68°12.6'W. This position is plotted and labeled with a small circle and the time.

Navigating an Underwater Robot

Autonomous Underwater Vehicles (AUVs) are often used to search for specific objects (such as shipwrecks) or features (such as hydrothermal vents). One advantage of AUVs is that they can perform repetitive search tasks while humans and ships carry out other activities. Before a search can begin, someone must decide on a path that the AUV should follow to adequately cover the area to be searched. This usually depends upon the time available for the search, and the area that can be covered by sonar or sensors used to detect the things that are the object of the search. Once a path has been decided, the computer that controls the AUV must be programmed to follow the desired path. This is often a sort of zig-zag across the survey area.

Suppose you wanted to survey a portion of Nautilus Shoal in the Chesapeake Bay, covering the area of the Shoal included inside the dashed rectangle in Figure 5 (a shoal is a shallow area within a body of water surrounded by deeper water). Your AUV has a survey speed of 4 knots (4 nautical miles per hour). You need to provide a set of instructions that tells the AUV where to start the survey, and then how long to run on a series of courses that will cover the area. You have decided to space your survey lines 0.2 nautical miles apart (this is fairly wide spacing, and would only be appropriate if you were looking for very large objects).

Figure 5. Survey Plan for an Underwater Robot



The following steps explain how you would create an instruction set for an AUV to do this survey. Figure 5 shows all of these steps. Your instruction set would begin with the starting location, which in this case is 37°03.0'N, 75°55.0'W. The first leg of your survey (labeled "1" in Figure 5) will have a course of 0° (due north). Looking at the latitude scale on the right side of the chart, you find that the shoreline is 1.4 nautical miles from the starting position (remember that one minute of latitude equals one nautical mile). So, the first leg of your survey should be 1.3 nm long. At 4.0 knots, your AUV will cover 1.3 nautical miles (nm) in

$$1.3 \text{ nm} \div 4.0 \text{ nm/hr} = 0.325 \text{ hr}$$

So your survey plan now has these steps:

1. Begin at 37°03.0'N, 75°55.0'W
2. Run on Course = 0° for 0.325 hr (Leg 1)

To make the next leg of your survey ("3"), your AUV needs to move 0.2 nm to the west. Measure 0.2 nm on the latitude scale, and draw a line parallel to Leg 1 that is 0.2 nm to the west. Now draw a line from the end of Leg 1 to the start of Leg 3, which should be 0.1 nm from the shoreline. This short line is Leg 2. Measure the length of Leg 2 (slightly more than 0.2 nm, but we'll use 0.2 nm for our calculations), and find the course by "walking" the direction of Leg 2 to the compass rose with a parallel ruler (the course for Leg 2 is 246°). Your AUV will cover 0.2 nm in

$$0.2 \text{ nm} \div 4.0 \text{ nm/hr} = 0.05 \text{ hr}$$

Find the length of Leg 3 using the latitude scale (about 1.2 nm). At 4.0 kn, your AUV will cover this distance in

$$1.2 \text{ nm} \div 4.0 \text{ nm/hr} = 0.30 \text{ hr}$$

The course for Leg 3 will be 180° (due south). So now you can add two more steps to your survey plan:

3. Run on Course = 256° for 0.05 hr (Leg 2)
4. Run on Course = 180° for 0.30 hr (Leg 3)

Continuing the same process, you would add Legs 4, 5, and 6 to your survey plan:

5. Run on Course = 270° for 0.05 hr (Leg 4)
6. Run on Course = 0° for 0.275 hr (Leg 5)
7. Run on Course = 257° for 0.05 hr (Leg 6)

To complete your survey plan, you would continue the same process until all the area on Nautilus Shoal inside the dashed rectangle was covered.

Now It's Your Turn!

Make a plan for a Phase 1 survey for ABE to prospect for hydrothermal vents along a portion of the Mid-Atlantic Ridge described in Yoerger *et al.*, 2007 and illustrated in Figure 6 (the stars show the location of active vent sites).

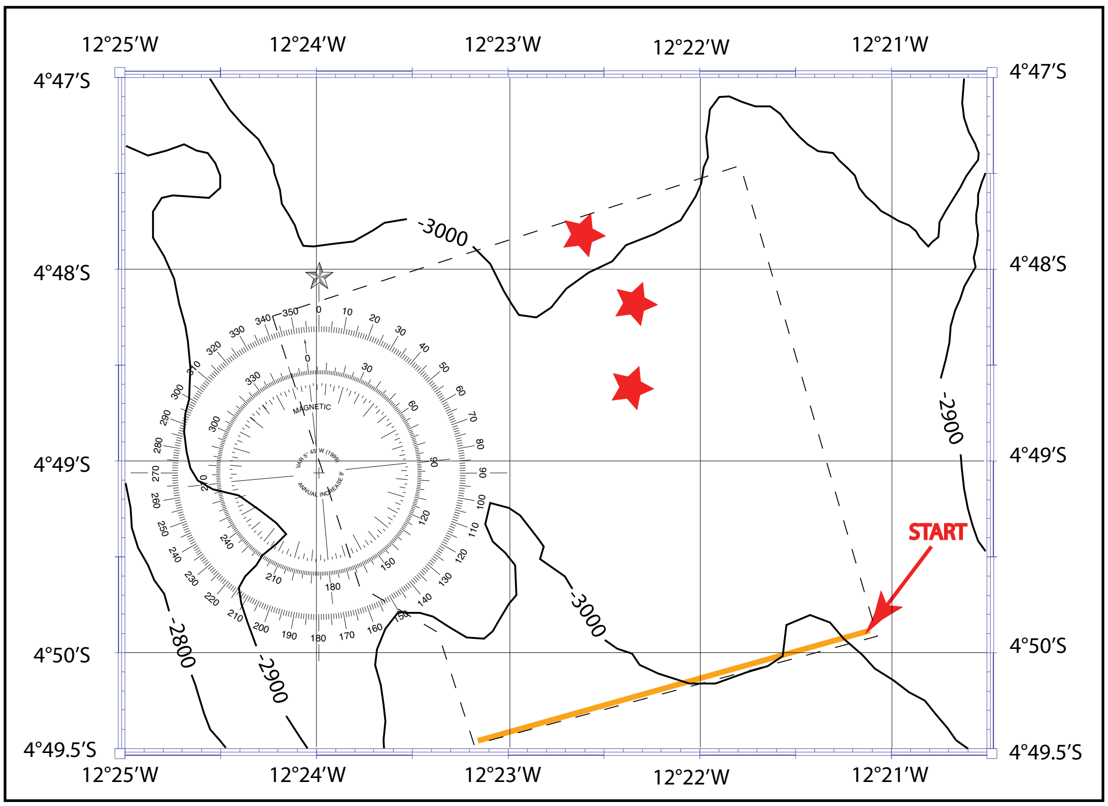
Assume ABE travels at a speed of 1.2 kn. Starting at the position indicated by the arrow in Figure 6, plan a survey that uses six tracks spaced 0.5 nm apart to survey the area inside the dashed lines.

The first leg of the survey is already drawn. The instructions for this leg of the survey are:

1. Begin at 4°49.9'S, 12°21.1'W
2. Run on Course = 254° for 1.75 hr (Leg 1)

Run five more survey lines parallel to the first leg. Draw your complete survey plan on Figure 6, and write the remaining instructions below.

Figure 6.



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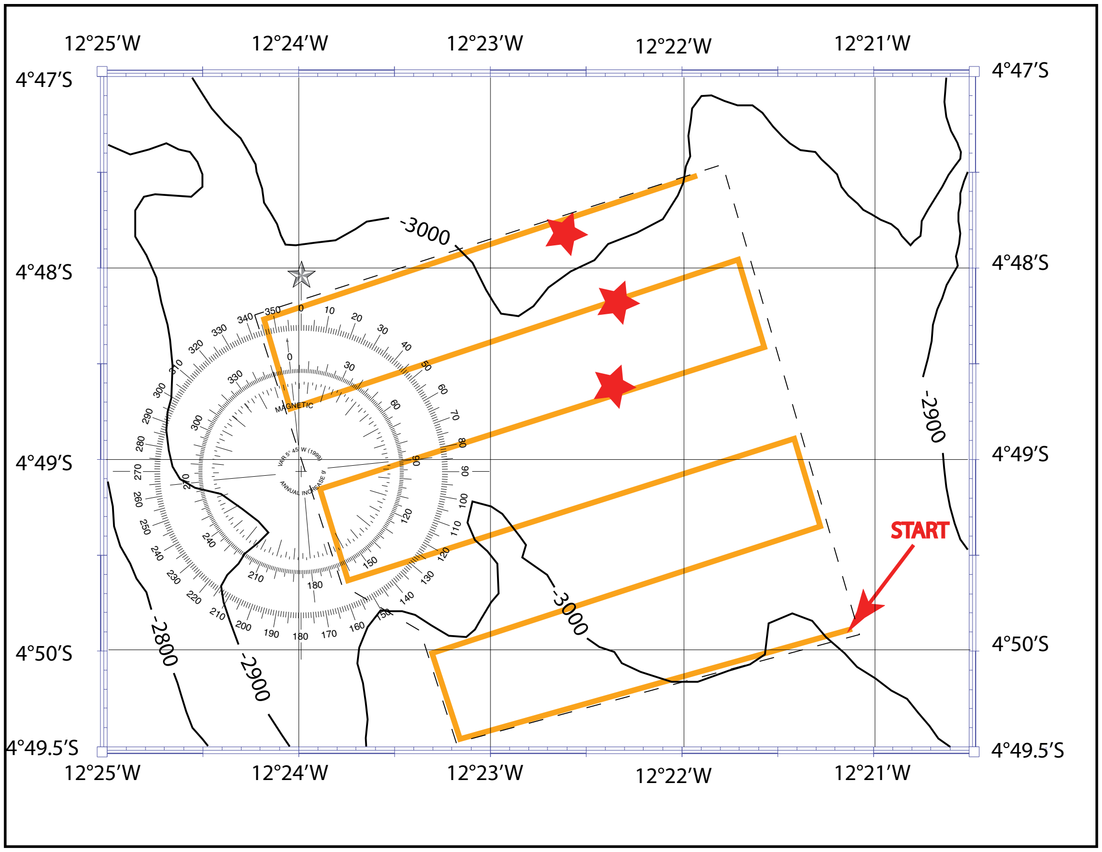
The Ridge Exploring Robot
Teacher Answer Key for Navigation with Nautical Charts



The completed instructions for the survey are:

1. Begin at 4°49.9′S, 12°21.1′W
2. Run on Course = 254° for 1.75 hr
3. Run on Course = 344° for 0.417 hr
4. Run on Course = 074° for 1.75 hr
5. Run on Course = 344° for 0.417 hr
6. Run on Course = 254° for 2.083 hr
7. Run on Course = 344° for 0.417 hr
8. Run on Course = 074° for 2.083 hr
9. Run on Course = 344° for 0.417 hr
10. Run on Course = 254° for 2.083 hr
11. Run on Course = 344° for 0.417 hr
12. Run on Course = 074° for 2.083 hr