Earth Calling…

Overview:

A hands-on activity exploring spacecraft radio communication concepts, including the speed of light and the time-delay for signals sent to and from spacecraft.

Target Grade Level: 6-8

Estimated Duration: 40 minutes

Learning Goals: Students will be able to…

- calculate the amount of time it takes for a radio signal to travel to a spacecraft using the speed of light.
- demonstrate the delay in radio communication signals to and from a spacecraft.
- devise unique solutions to the radio-signal-delay problem.
- compare their velocity to that of the spacecraft and the speed of light.

Standards Addressed:

Benchmarks (AAAS, 1993, 2008)
  The Nature of Technology, 3A: Technology and Science, 3C: Issues in Technology
  The Designed World, 8D: Communication
National Science Education Standards (NRC, 1996)
  Science and Technology, Standard E: Abilities of technological design,
      Understandings about science and technology

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Teacher Background:

While some spacecraft return to Earth with valuable data as part of their cargo, all require some periodic remote communications as they travel. And for those spacecraft that do not return to Earth, the communication system is our only link to the valuable data collected during its journey.

Not only do spacecraft transmit valuable data, but also spacecraft 'health' information is returned to Earth via these communication systems. It is important to know that the spacecraft's power systems, heating and cooling systems, and instruments are all operating as expected. And of course signals must be sent to tell the spacecraft where to go or which instrument to operate and when via this system. Such course correction and data collection commands become even more critical as the spacecraft approaches its 'destination,' where such maneuvers become progressively finer and many of the science goals are to be achieved.
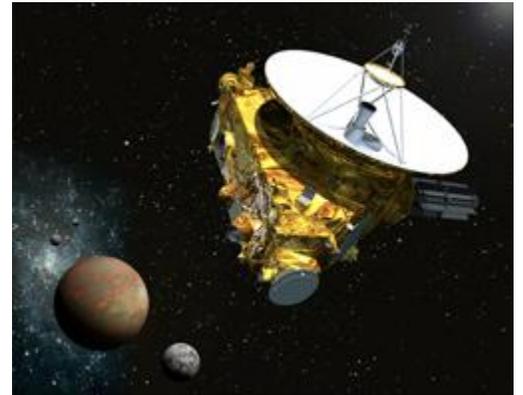

Figure 1. An artist's rendering of the New Horizons spacecraft as it approaches Pluto. The prominent 2.1-meter dish antenna is used to communicate with Earth from up to 7.5 billion kilometers away. (Image credit: JHUAPL/SwRI)

Each mission has its own telecommunications system design, but all use radio waves to transmit signals. Radio waves, like light waves, are part of the electromagnetic spectrum.
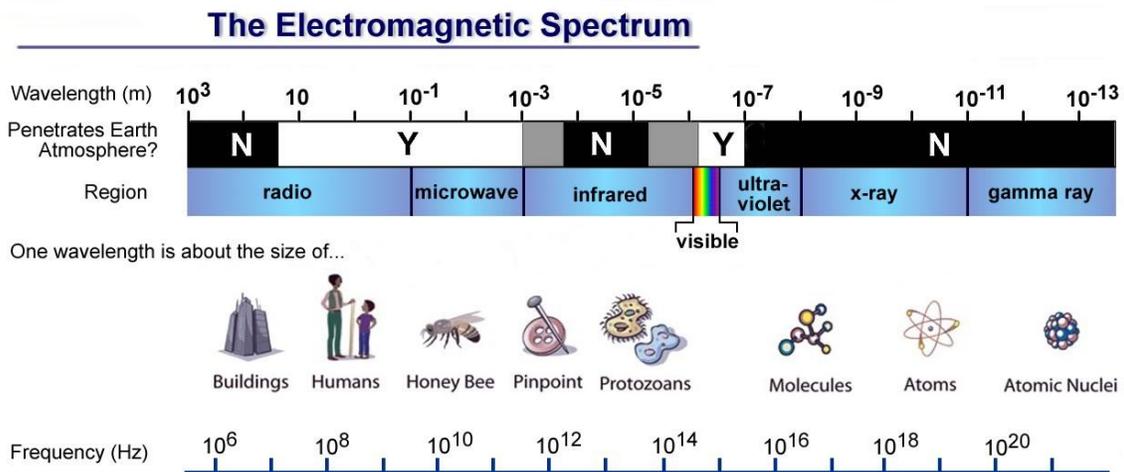

Figure 2. The electromagnetic spectrum. Notice radio waves penetrate Earth's atmosphere, have long wavelengths, and low frequencies. (Image courtesy: NASA).

As you can see in Figure 2, radio waves have long wavelengths, low frequencies, and—important for our ground-based communications—they penetrate Earth's atmosphere. Radio waves don't require as much energy for the spacecraft to produce as shorter wavelength electromagnetic waves do, which allows for more energy to power the instruments and other systems on a spacecraft. And unlike x-rays and shorter wavelengths, you don't have to protect yourself from them because they are harmless to humans. All of these characteristics make radio waves an ideal choice for carrying

signals to and from spacecraft, as well as for carrying signals here on Earth for our TVs and radios.

Like all waves of the electromagnetic spectrum, radio waves travel at the speed of light. The speed of light in a vacuum is 299,792,458 meters per second, often approximated simply as 3×10^8 m/s. It is usually denoted by the symbol *c*, for the Latin *celeritas,* meaning "swiftness." Here on Earth, when you turn on the light switch the light seems to reach your eyes instantaneously. However, if you happen to be a mission operations flight controller sending an important command to a spacecraft—a signal that must travel many billions of kilometers—even the speed of light can seem slow.

While sending a radio signal to the moon takes only a little over a second, the delay in communication is far more dramatic with a spacecraft traveling to, say, Pluto and beyond. To better understand how we communicate with a spacecraft, let's pretend we want to send a command to the New Horizons spacecraft telling it to take a picture of Pluto as it passes in July of 2015. Here is what the process of sending this command might look like:

> The science team member responsible for the camera to be used to take the picture must provide specific details of how the spacecraft should be oriented, when to turn the camera on and off, etc. to the Science Operations Center (SOC).

> The SOC team members translate those objectives into a language understood by the spacecraft, a process known as "sequencing." Since it is very important there are no errors, the translated command is first sent to a simulator for testing. If the spacecraft simulator reacts to the command as desired, the "sequenced" command can be sent to the Mission Operations Center (MOC).

> The MOC communicates "directly" with the spacecraft. Sending a command "up" to the spacecraft is called "uplink." The MOC needs a bit of help uplinking, though. They actually send the command to a system of very sophisticated antennas distributed around the world called the Deep Space Network (DSN).

> The three DSN facilities are positioned around the globe approximately 120 degrees from each other so that as Earth rotates at least one antenna is always "visible" from the desired area in space. The command is sent to the DSN and from there it is sent from the appropriate antenna to the spacecraft.

> The radio signal travels at the speed of light (about 3×10^8 m/s) to the spacecraft, which is standing by listening for commands. How long does it take, you might ask, for the radio signal to reach the New Horizons spacecraft at Pluto, nearly 3 billion miles (4.6 billion km) from Earth? About 4.5 hours! I hope you planned on this delay when you sent the message to take a picture of Pluto!

The signal from the spacecraft is very weak by the time it reaches Earth, since its energy has spread over a wider and wider area as it travels outward from the transmitter. In fact,

Figure 3. The 70-meter (230 feet) antenna at the Goldstone Deep Space Communications Complex in the Mojave Desert, California. This is one of many radio antennae at Goldstone, which is one of the three facilities that make up NASA's Deep Space Network. (Image courtesy: NASA/JPL)

the Earth-based antenna operated by the Deep Space Network must be able to detect a signal as weak as a millionth of a trillionth of a watt. If you stored energy transmitted at that rate for 40,000 years you could still light a Christmas tree bulb for only about 3 millionths of a second!

The signal from the spacecraft is not only extremely faint, it is embedded in a background of electromagnetic "noise." This is the incoherent background radiation produced by all other objects in the universe. It is always present in space, like static on your radio. Even while the New Horizons signal becomes fainter as the spacecraft gets farther away, the background noise remains at a roughly constant level. So the farther away the spacecraft, the more difficult it becomes to distinguish its signal from the noise. In addition, the communication equipment introduce their own noise.

How, then, can New Horizons communicate the data that it gathers as its instruments focus on Pluto, Charon, and the Kuiper belt neighborhood back to us at all? The answer is that New Horizons must slow down its data transmission rate (the number of bits per second) as it gets further and further away. To be understood back here on Earth, New Horizons must "talk" more slowly as its signal becomes weaker.

The receiver does this by steadily making measurements—many each second—and averaging the results. But each time, of course, it is measuring not the signal alone, but the signal plus the noise. The averaging process preserves the signal (suppose for example it is "on" during the measurements) but it tends to reduce the effect of the noise. That's because a measurement of the noise is as likely to give a positive result as it is to give a negative one, and so the noise measurements can cancel each other out in the average. That cancellation is more and more effective the longer the averaging process goes on.

How much cancellation is needed? Basically, the averaging has to continue until the average of the noise is so low that "one" and "zero" can be distinguished from one another in the signal. The signal-to-noise ratio (SNR) compares the power level of the desired signal with that of the noise. A larger SNR indicates a stronger signal—that is, one that is easier to distinguish from the background. Therefore, the smaller the SNR, the more averaging that is needed. But increasing the averaging time means that the "ones" or "zeros" from the signal have to persist for a longer time too, or else they will cancel each other out as well. The result is that a long averaging time, which is needed to reduce the effect of the noise, requires a decreased data transmission rate.

Figure 4. The online interactive at: http://patchyvalleyfog.com/signal_noise/ allows you to explore the concept of "signal-to-noise ratio" in greater detail.

This can be likened to talking very slowly when trying to carry on a conversation in a crowded, noisy room. By comparison, if you connect to the internet with DSL or broadband cable modem, you "uplink" and "downlink" at a rate measured in "megabits" or million bits per second! At 1000 bits per second, it will take about 4 hours to

downlink a picture of Pluto (and this is in addition to the time it takes to travel from the spacecraft to .

Communications with spacecraft are essential for successful missions. We need to monitor the heath of the spacecraft, uplink commands, and downlink data via these telecommunications systems. Information is sent and received using radio waves, which are ideal since they have long wavelengths, low frequencies, they don't require much energy to produce, and they penetrate the Earth's atmosphere. Unfortunately, spacecraft aren't the only objects in space emitting radio waves. Along with the data we receive from spacecraft also comes "noise," which must be distinguished from the data. This, among other reasons, is why it requires many people working together to take pretty pictures and collect valuable data of the planets and other objects in the universe we set out to explore.

Materials:

- free online metronome from http://www.metronomeonline.com/ or an actual metronome
- copy of some or all of **Planetary Images** pages (1 planet/page per group)
- copy of **Commands** (3 sets of 4 commands per group, there are 6 sets per page)
- copy of **"On a Mission" Student Data Sheet** (1 per group)
- tape (1 small piece per group, more if necessary)
- meter sticks (1 per group, if possible)
- stop watches (1 per group, if possible)
- transparency (or computer projection) of **How to take a picture of Pluto** sheet

Procedure:

Brief overview…

  What the teacher will do: The teacher will introduce some of the concepts of spacecraft communication and then briefly explain the **Delayed Communication** hands-on activity. The teacher will then divide the class into groups so that each group has a "spacecraft," 2 or 3 "signal carriers," and at least one "mission control officer" (note: for groups larger than five, assign additional students to be "mission control officers.") With help from the students, he/she will arrange the classroom as indicated in the **In-Class Procedure** section, below. Once groups are in place, the teacher can go over the rules for each role using the instructions on the **On a Mission** student data sheet. Then the teacher will begin the metronome and observe the groups as they perform the activity. The teacher will initiate the inquiry portion of the activity after groups have accomplished the first mission. After about 5 minutes of inquiry time, the teacher will observe groups as they perform the mission again using their unique solutions. Finally, groups will be allowed to finish the **On a Mission: Part Two**, which can be used for assessment.

  What the students will do: After learning about spacecraft communication, students will help the teacher arrange the classroom for the activity, as indicated above. The teacher will distribute the **On a Mission** student data sheet and go over the rules for each role. Students will be assigned to groups, which will then "race" to collect data from their planets (a picture of that planet) and return to their respective "mission control centers" using specific instructions and restrictions outlined in the **On a Mission** student data sheet. Then the groups will devise a unique method to command the spacecraft that avoids the delay in communication. They will test their unique solution in a second trial of the activity. After all groups have completed their missions, students will participate in a discussion about the delay in spacecraft communications and how this might affect missions and finally they will complete **On a Mission: Part Two**, which can be used for assessment purposes.

Advance Preparation

1. Either locate a metronome or use the URL provided in the **Materials** section for the free online metronome using computer speakers loud enough for the whole class to hear.
2. Make copies as directed in the **Materials** section.
3. Cut **Commands** sheets apart; there are 4 commands total with 6 sets of commands per sheet. Each group needs 3 sets of commands or half a page.

In-class Procedure

1. Introduce some of the concepts of spacecraft communication, using the **Background** section above if desired.
2. Show students the **How to take a picture of Pluto** transparency/computer projection. Explain that this is how to command the spacecraft to take a picture, but it does not illustrate how we then retrieve the picture/data collected. Tell them that they are going to learn more about the challenges of spacecraft communication in a hands-on activity.
3. Divide the class into groups of about 4-6 students. Further divide each group as follows:
   a. 1 spacecraft
   b. 2 or 3 signal carriers
   c. At least 1 mission control officer
4. With help from the students, arrange the classroom by moving aside tables and chairs so that each group has a "mission control center" (simply a space to gather) that is a few meters from a chair or spot on the floor to which you will attach their planet (picture). (See Figure 4, below).
   Note: to create a more competitive "race-like" atmosphere, arrange groups side-by-side so that all have a common starting line and are the same distance from their planet. Also, if no table is being used you may want to outline "mission control centers" using masking tape on the floor so it is clear that the "mission control officers" stay within the mission control boundary when they send commands via the "signal carriers."
5. Tape one of the **Planetary Images** to a chair or to the floor a few meters from each "mission control center" and distribute **Commands** and **"On a Mission" Student Data Sheets** to each group.
6. As a class review the instructions for each of the different roles in the **"On a Mission" Student Data Sheets**. Be sure to remind the groups that it may take more than one orbit to accomplish the goal of collecting the data/picture before returning to the mission control center depending on how well the signal carriers time the delivery of their commands. You might also wish to share this diagram with them if there is still some confusion, after going over the directions with them.
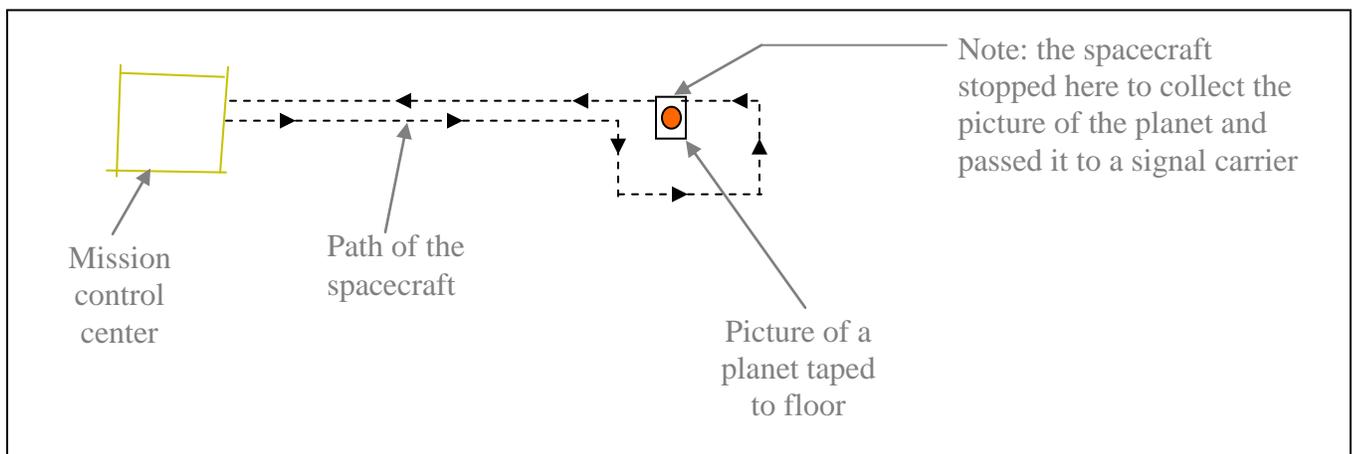

Figure 5. Diagram of an ideal potential mission "trajectory" from a bird's eye view. The paths that students take will be much more circuitous that this path!

7. Start the metronome and let the races begin! Move between the groups as they perform the activity, making sure they are following directions.

8. After all groups have accomplished their missions successfully, ask students to return the picture of their planet to its previous location on the floor/chair and gather at their mission control centers. Explain that engineers have worked to solve the challenges that a delay in communication can cause. Working as a team, groups should now spend about 5 minutes devising their own unique solutions to the delayed command problem. Explain (and perhaps write on the board) what they can and cannot change, as follows:

   CAN NOT CHANGE: speed of the spacecraft, speed of light, distance between mission control and the picture of the planet

   CAN CHANGE: the number of commands the "signal carrier" leaves mission control with to deliver to the spacecraft, they can create a new command, either the spacecraft or the signal carrier can deliver the picture of the planet to the mission control center after it has been collected.

   Provide several meter sticks, tape, and stop watches for their use and allow them to move between their mission control centers and planets as they come up with solutions.

9. After about 5 minutes of inquiry time, ask groups to return to their mission control centers to perform their mission again, but this time using the solutions to the delay in communications that they devised. Be sure to note which team finishes first, second, etc. since this will be the order of reporting in the next procedure (number 10).

10. Once groups have completed their missions using their unique solutions, ask them to report their solutions with the team finishing in first place reporting first, the team that finished second reporting second, etc. Facilitate discussion about the solutions. Some questions may include: why were some able to complete the mission faster, which solutions were particularly simple or elegant, and—knowing what they know now—what might work even better?

11. Finally, ask them to work together to complete the second part of the student data sheets: **On a Mission: Part Two**. (See the answers for this on page 24, **On a Mission: Part Two—TEACHER ANSWERS**). This can be collected and used for assessment of the activity.

Extensions and Adaptations:

- **Have students calculate the distance their spacecraft traveled**. In the second part of the hands-on activity (see #8 in the In-class Procedure section) add to the complexity by asking students to determine a way to measure the total distance traveled by the spacecraft. If they need hints, explain that they are walking at a fixed speed with one foot immediately in front of the other with every other tick of the metronome. They can calculate this fixed speed by measuring the length of the spacecraft person's foot and the number of seconds in two ticks of the metronome. (Speed = (change in distance or length of foot)/(change in time or seconds in two ticks of the metronome)). If they record the total travel time for the spacecraft they can then calculate the distance with:

    change in distance (unknown) = (fixed speed (calculated above)) x (total travel time of spacecraft)

    or   distance = speed x time

References:

- For more information about the Deep Space Network, visit their website:
  http://deepspace.jpl.nasa.gov/dsn/
  Or, for a student-version of their website:
  http://spaceplace.nasa.gov/en/kids/dsn_fact1.shtml
- The New Horizons Science Operations Center (SOC) website with a brief tutorial about spacecraft communication and the role of the SOC:
  http://pluto.jhuapl.edu/science/soc.php
- The NASA Jet Propulsion Laboratory "Basics of Space Flight" has a chapter on Telecommunications that may be useful background reading material for the teacher:
  http://www2.jpl.nasa.gov/basics/bsf10-1.php
- The NASA Space Place has a short video about spacecraft communication that may be a useful resource for the students and teachers alike:
  http://spaceplace.nasa.gov/en/kids/st5xband/st5xband.shtml
- Additional background information and an activity exploring waves and phases, called "Speaking in Phases":
  http://spaceplace.nasa.gov/en/educators/dsn_signal_mod_web.pdf

Standards:

National Science Education Standards (NRC, 1996)

Content Standards: 5-8
 Science and Technology, Content Standard E:
- Abilities of technological design
- Understandings about science and technology

Benchmarks (AAAS, 1993, 2008)

Chapter 3. The Nature of Technology
 A. Technology and Science, Grades 6-8:
- Technology is essential to science for such purposes as access to outer space and other remote locations, sample collection and treatment, measurement, data collection and storage, computation, and communication of information.

 C. Issues in Technology, Grades 6-8:
- The human ability to shape the future comes from a capacity for generating knowledge and developing new technologies—and for communicating ideas to others.
- Scientific laws, engineering principles, properties of materials, and construction techniques must be taken into account in designing engineering solutions to problems.

Chapter 8. The Designed World
 D. Communication, Grades 6-8:
- Information can be carried by many media, including sound, light, and objects. In the 1900s, the ability to code information as electric currents in wires, electromagnetic waves in space, and light in glass fibers has made communication millions of times faster than mail or sound.

spacecraft, using the "heliocentric velocity" found here: http://pluto.jhuapl.edu/mission/whereis_nh.php (Record both velocities below).

4. Calculate the velocity of one of your signal carriers during the "On a Mission" activity using the heel-to-toe method of travel with EVERY tick of the metronome. Compare the signal carrier velocity with the speed of light, and record both below.

5. In the "On a Mission" activity, the signal carriers traveled at a rate that was called the speed of light, although in #4, above, you found that the velocity of the signal carriers and the actual speed of light are quite different. During the activity the signal carriers only had to travel this speed when they were DELIVERING a command to the Spacecraft or delivering data to the Mission Control Center. When they were not acting as a radio wave (i.e. not delivering a command or data) they did not have to travel at the "speed of light." Is this ever true of real signals sent to and from spacecraft?

6. As a group, evaluate your performance during the "On a Mission" activity:

    a. What was the most challenging aspect of this activity?

    b. How did your group solve this challenging problem?

    c. When your group was asked to devise another solution to the delay in communication problem and perform the activity again, how did you finally choose one solution over the alternatives?

    d. Were all group members able to share their ideas equally?

On a Mission: Part Two—TEACHER ANSWERS

Note: the first part of this Student Data Sheet is the instructions for the activity, so there are no answers.

1. Calculate the time it takes to send a radio signal to the New Horizons spacecraft when it is near Pluto. (Note: the distance to Pluto is 4.6 billion kilometers). Report your answer in hours.

Distance = 4.6 billion kilometers
Speed of light ≈ 3 x 10^8 m/s

$$t = \text{distance/velocity} = \left(\frac{4.6 \text{ billion km}}{3 \times 10^8 \text{ m/s}}\right) \cdot \left(\frac{1000 \text{ m}}{1 \text{ km}}\right) \cdot \left(\frac{1 \text{ hr}}{3600 \text{ s}}\right) = 4.3 \text{ hrs}$$

2. Based on your calculation in #1, how long will it take to send a signal to the spacecraft near Pluto and receive a confirmation signal in return from the spacecraft?

2 * 4.3 hrs = 8.6 hrs

3. Calculate the velocity of your spacecraft during the "On a Mission" activity using the heel-to-toe method of travel with every other tick of the metronome. Compare the velocity of your spacecraft with the current velocity of the New Horizons spacecraft, using the "heliocentric velocity" found here: http://pluto.jhuapl.edu/mission/whereis_nh.php (Record both velocities below in the same units).

Answers will vary, but generally they can measure the distance they traveled (i.e., distance) during a set time (i.e., 30 sec) or they can measure the length of the foot of the person acting as the spacecraft (i.e., distance) and the time of two ticks of the metronome (since it traveled one heel-to-toe length every other tick of the metronome) and plug the values into the equation as follows: v = distance/time

The velocity of the spacecraft is found at the above URL near the upper right of the image and is currently 16.32 km/s.

4. Calculate the velocity of one of your signal carriers during the "On a Mission" activity using the heel-to-toe method of travel with EVERY tick of the metronome. Compare the signal carrier velocity with the speed of light, and record both below in the same units.

Again, answers will vary. They can use the same method as they used in number 3, above, however now they are traveling with every tick of the metronome instead of every other, so the time would be just 'one tick' instead of two if using the second method.

The speed of light is about 3 x 10^8 m/s.

5. In the "On a Mission" activity, the signal carriers traveled at a rate that was called the speed of light, although in #4, above, you found that the velocity of the signal carriers and the actual speed of light are quite different. During the activity the signal carriers only had to travel this speed when they were DELIVERING a

command to the Spacecraft or delivering data to the Mission Control Center. When they were not acting as a radio wave (i.e. not delivering a command or data) they did not have to travel at the "speed of light." Is this ever true of real signals sent to and from spacecraft?

No! Outside of very unique laboratory conditions the speed of light is always about 3 x 10^8 m/s and radio waves always travel at that speed.

6. As a group, evaluate your performance during the "On a Mission" activity:

Answers will vary