

ANGLING FOR GAMMA-RAY BURSTS

About this Poster

The Swift Gamma-Ray Burst Explorer is a NASA mission which will observe the highest energy explosions in the Universe—gamma-ray bursts (GRBs). During Swift's 2-year nominal mission it will detect and follow-up on hundreds of these explosions, vastly increasing scientists' knowledge of these enigmatic events.

Education and public outreach (E/PO) is also one of the goals of the mission. The NASA E/PO Group at Sonoma State University develops classroom activities based on the science of the Swift mission. This poster and activity are part of a larger Educators' Guide called "Gamma-Ray Bursts" which is aimed at grades 9-12.

The front of the poster is an artist's illustration depicting three satellites detecting a burst of gamma rays from a distant GRB. The satellites are all located at different distances from the GRB, and so detect it at different times. This is the basis of the activity, below, "Angling for Gamma-Ray Bursts." This activity uses the delay in the detection times between satellites to determine the direction to the GRB. The activity is complete and

ready to use in your classroom; the only extra materials you need are a calculator, a ruler, graph paper, and a pair of scissors. The activity is designed and laid out so that you can easily make copies of the student worksheet and the other handouts.

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The Swift Education and Public Outreach website is <http://swift.sonoma.edu>. This poster and other Swift educational materials can be found at:

<http://swift.sonoma.edu/education/>

Introduction to Gamma Rays and Gamma-Ray Bursts

The **electromagnetic spectrum** comes in many flavors, from low-energy radio waves, through microwaves, infrared, visible light (the only part of the spectrum we can see with our unaided eyes), ultraviolet, X-ray, and finally extremely high-energy gamma rays (*Figure 1*). Astronomical objects of different sorts emit some or all of these kinds of **radiation**, and we can only get a complete picture of these objects by studying them in all the different regions of the electromagnetic spectrum.

The type of radiation emitted by an object tells us quite a bit about it. Low energy or relatively cold objects like planets and dust clouds emit mostly radio or infrared waves, which are low-energy waves. Hotter, more energetic objects like stars and nebulae can emit higher energy waves in the visible and ultraviolet range. Even more energetic objects like **pulsars** (the collapsed cores of stars that exploded as **supernovae**), extremely hot gas, and **black holes** can emit X-rays. But to emit gamma rays you need something incredibly energetic, something that dwarfs the energy emitted by “cooler” objects. Some pulsars which have unusually intense magnetic fields can generate gamma rays. The fierce magnetic energy in a huge **solar flare** can (very briefly) generate gamma rays. Twisted magnetic fields from spinning supermassive black holes can channel particles and accelerate them to velocities near light speed, generating focused jets of gamma rays.

But even these pale in comparison to **gamma-ray bursts (GRBs)**. In the 1960s, the United States was concerned that other countries might test nuclear weapons in near-Earth space, despite a treaty to ban such events. Nuclear detonations produce bursts of gamma rays, so the U.S. military launched a series of satellites designed to detect these high-energy explosions. To their surprise, scientists soon began detecting dozens

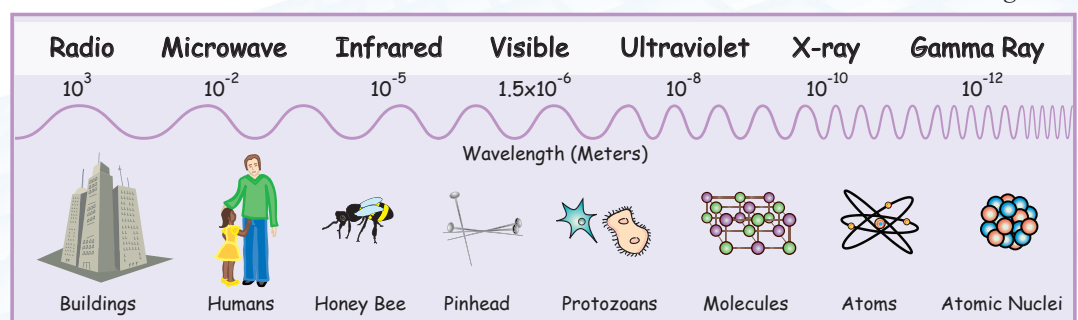


Figure 1

of explosions, but discovered they were not coming from the vicinity of the Earth: these bursts were occurring in deep space.

The source of these bursts was a mystery (and to some extent still is today). Some bursts last for only milliseconds, while others drag on for seconds or minutes. At first astronomers assumed these must be “local” phenomena—somewhere in our own **Milky Way Galaxy**. Because of the energy involved in producing such a large number of gamma rays, a distant object would have to be unimaginably powerful to account for a GRB.

However, it became clear with time that GRBs were indeed coming from vast distances, and were therefore sources of enormous energy. In fact, there is only one kind of object known that can generate that kind of energy: a black hole. Most people don’t think of black holes as being able to blast energy *out*; they think that black holes can only draw matter *in* due to their enormous gravity. But in fact it’s their gravity that can make them so energetic! When a black hole forms, the overwhelming gravity accelerates matter very strongly, giving that matter tremendous energy. Through complicated physical processes, that energy from the infalling matter can be converted to gamma rays and released in one fierce blast. This means, in essence, that GRBs are the birth cries of black holes.

GRBs appear without warning somewhere on the sky at least once every day, indicating that somewhere, far off (we hope!) in the Universe a black hole is born. NASA’s Swift mission will allow scientists to study GRBs better than ever before. It is very difficult to locate the direction to a GRB using gamma rays alone, since gamma rays cannot

be focused like lower-energy light, and the burst itself may only last a fraction of a second. For many years, the best way to localize a GRB on the sky was to use a fleet of satellites which had gamma-ray detectors on board. This method is outlined in the activity below.

Recent advances in gamma ray detector technology have made great improvements on this method. Also, some GRBs are followed by a fading **afterglow** of light which can be seen in X-rays, optical, infrared, and even radio wavelengths. Follow-up observations of this decay allow astronomers to better pinpoint the direction to the GRB and even look into its local environment. The Swift satellite will quickly lock on to GRBs, using the gamma ray-sensitive Burst Alert Telescope to get a rough location in seconds, and a more accurate one within minutes as its X-ray and Ultraviolet/Optical Telescopes image the target. The information on the location and strength of the GRB will be relayed to the ground to allow faster and more detailed follow-up observations of the rapidly fading catastrophe. Astronomers hope they will get enough data to finally solve the riddle of these explosions that are so vast that they equal the energy of a billion *billion* (10^{18}) Suns.



Science Concepts:

1. Satellites can be used to determine the time when a GRB occurs, and this information can be used to get the direction to the GRB.
2. It takes several satellites using time delays to accurately get the direction to the GRB.
3. Light travels in a straight line and at a constant speed in a vacuum. From a distant object, the light rays are parallel.

National Science Education Standards

Content Standard A: Science as Inquiry

- Abilities necessary to do scientific inquiry

Content Standard B: Physical Science

- Interactions of energy and matter
- Motion and Forces

Content Standard D: Earth and Space Science

- Origin and evolution of the universe

Content Standard E: Science and Technology

- Abilities of technological design

Content Standard G: History and Nature of Science

- Science as a human endeavor
- Historical perspectives

Assessment:

Points	Graph	Calculations	Reflections
4	Graph is accurate	Calculations are all accurate	Answers are complete, correct, and reflective
3	Graph is adequate	Most calculations are accurate	Answers are correct, but incomplete or not reflective
2	Graph is somewhat inaccurate	Some calculations are accurate	Some answers are incorrect, incomplete or not reflective
1	Graph is inaccurate	Calculations are inaccurate	Answers are incorrect
0	No graph turned in	No calculations completed	None turned in



Angling for Gamma-Ray Bursts Activity

Duration:

Introduce concepts: 30 min

Perform activity: 1 hour

Objectives:

- Students will be able to explain at least two properties of light and how it travels through space.
- Students will be able to use time differences to determine directions to gamma-ray bursts.
- Students will be able to explain how astronomers use multiple satellites to determine the direction to gamma-ray bursts.

Background Information

Note for the Teacher

[This information is split up into a section for you, and one for the students to read. You will of course need to read the student portion as well. It is included in the **Student Handout** section. The information provided to the student is sufficient to do the exercise, but the additional information given to you below will complement the student's understanding of how the direction to a GRB is triangulated. Going over this information with the students the day before they perform the exercise will increase their understanding of the activity and its concepts.

Remember to emphasize the point that the people in the following analogy are hearing sound waves, not light waves. Sound waves are transmitted through a medium (such as air) while light waves (also known as photons) are not, and can travel through the vacuum of space. Also, in this analogy, it is important to stress the difference in speed between sound and light waves, and that the lightning and thunder occur simultaneously.]

Imagine you are outside and a storm is approaching. There is a flash of lightning, and a few moments later — say, ten seconds — you hear the thunder. The flash of light traveled from the lightning bolt to you in less than a millisecond, since the speed of light is 300 million meters per second. But the sound waves are much slower, around 300 meters per second, so they take an appreciable amount of time to reach you, even though the lightning and thunder occurred at the same time.

If a friend stands a few hundred yards to your left *but the same distance to the lightning bolt as you*, she will hear the thunder at the same time you do. Since you are both the same distance from the lightning, it takes the same amount of time for the thunder to reach you. If you mark the time when you hear the thunder, then compare watches, you will see you heard it at the same time. That means the wave front of the thunder was traveling perpendicularly to the line between you and your friend (Figure 1).

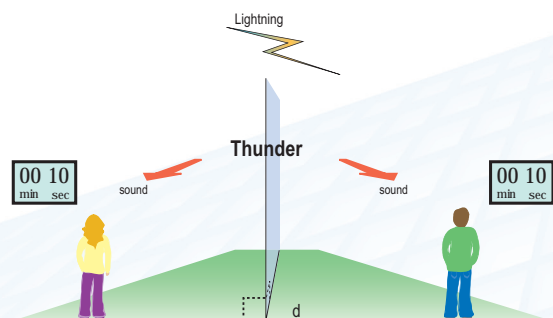


Figure 1

Essential Question:

How can the directions to gamma-ray bursts be determined using the properties of light?

If your friend now stands a few hundred meters away from you, *farther* from the lightning, she will hear the thunder *after* you do, because it takes time for the sound wave to pass you and reach her. When you compare watches, you can see that she heard it after you (Figure 2).

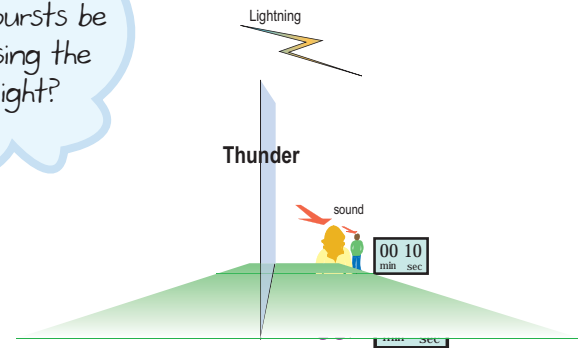


Figure 2

So the minimum time delay (0 seconds) happens when a line between you and your friend is perpendicular to the direction that the sound travels. The maximum delay (the distance between the two of you divided by the speed of sound) happens when the line between you is parallel to the direction the sound is traveling. If the line between you is at an angle to the sound direction, the time delay will be somewhere between the minimum and maximum (Figure 3). In fact, the time delay depends on that angle.

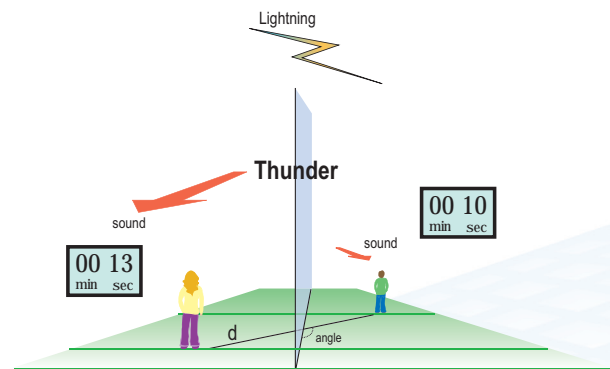


Figure 3

So, if you know the distance between the two of you, the direction to your friend, the speed of sound, and the delay between the times you heard the thunder, you can calculate the direction to the lightning.

In this activity, the locations in space of different satellites are analogous to the positions of you and your friend(s). Because the satellites are so widely separated, we can use the delay in the arrival times of the light rays to triangulate the direction to a cosmic gamma-ray burst, just as the direction to the lightning was triangulated in the analogy above using sound waves (thunder).

Materials for each group of 2 or 3 students:

- Ruler
- Scissors
- Pencil
- Protractor
- Light rulers (assembled in activity)
- Graph paper (preferably 0.5 cm/square)
- Calculator

Materials for each student:

- Student Worksheet
- Student Handout

Procedure:

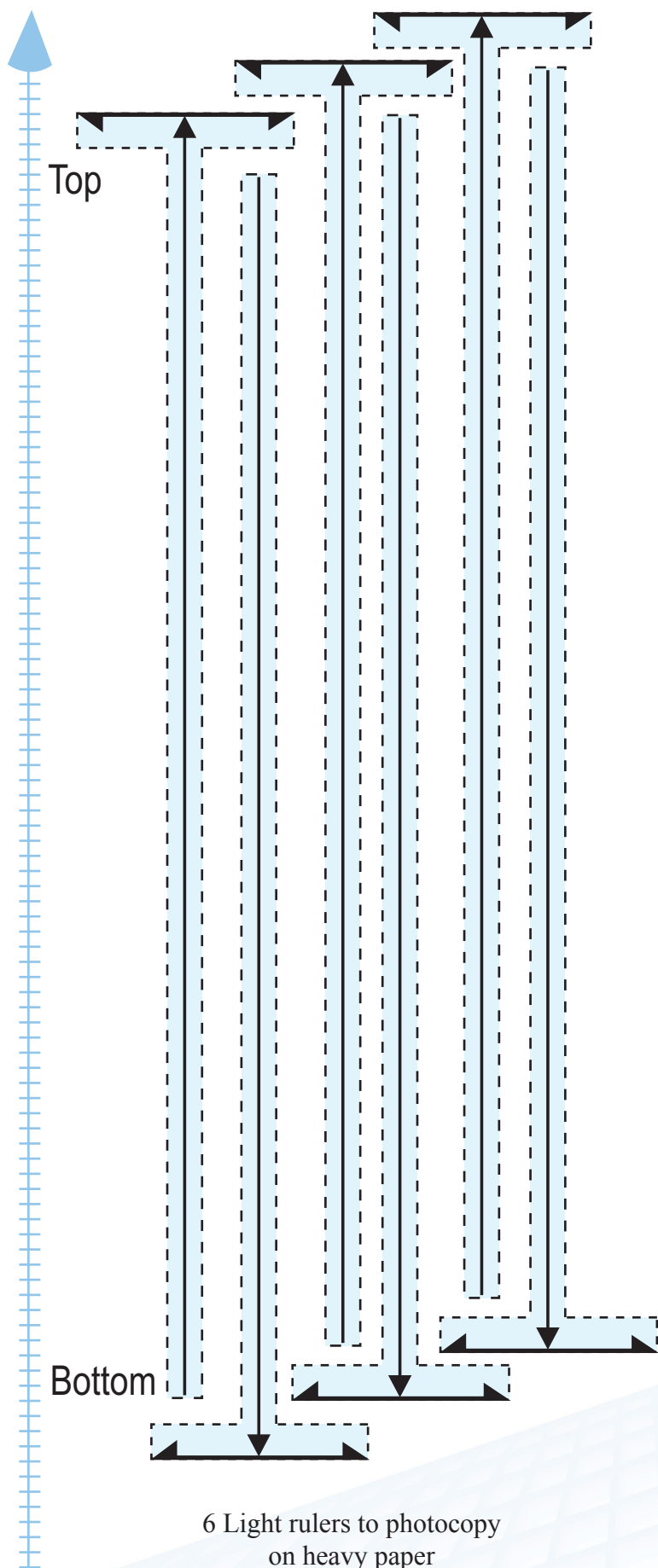
- 1) **Pre-class:** make copies of the Handouts (which can be reused), and the Student Worksheets, one per student. Make copies of the light rulers on card stock (using regular paper makes it difficult to manipulate the light rulers). Make sure each group gets one or two extra light rulers in case they make a measuring or cutting mistake.
- 2) At least one day before the activity is performed in class, give the students the Student Handout. As homework, have them read it carefully and write out a paragraph describing the procedures of the activity. You can also assign the Extension Activity (see below) as homework before the activity is done.
- 3) Explain to the students that they will be using the time delays between satellite detections of a gamma-ray burst to find the direction to the burst.
- 4) Go over the material in the introduction above. Use the thunder analogy (from the Background Information section) with diagrams to make sure they understand the concept. The illustration on the front of the poster will also be helpful. To print images on transparency, see: <http://swift.sonoma.edu/education/grb/transparency/>
- 5) **In-class:** Perform the activity. Note that at the end of the Student Handout is a Math Extension exercise. This is for students who are learning more advanced trigonometry, and can be considered “extra credit.” When your students get to step 2 and they are all trying to find the solutions, walk around the classroom and assist them with lining the T rulers up.
- 6) **Wrap up/reflection:** After the activity is completed, have the students break up into different groups of three and discuss their results. How are their individual results alike, and how are they different? What are possible sources of error, and what might be the biggest ones? After a few minutes, break up the groups so the students can have individual reflection time. Have them think of where else this activity might be useful. Some examples could be finding the direction to a thunderstorm, surveying, and earthquake measurements. How would your students set up an experiment to use this method in those cases?

Transfer Activities:

- A. Using the example of two people listening to a thunderstorm, have the class make a plot showing the time delays measured between the two people as the angle between them and the direction to the lightning changes from perpendicular to parallel. They can measure this directly by using scale drawings. Have them describe the plot. Does it look familiar to them? The delays should fall along (half of) a sine curve.
- B. Lead a discussion about how this activity could be modified to include the third dimension. Topics could include how many satellites would be needed (answer: 4), how the light rulers would need to be modified (or changed completely) to accommodate the new dimension, and how you would calculate the angle to the GRB from the Earth.

Extension Activities:

- A. Have the students research GRBs and write a short (1 page) report on some aspect of them. This can include how they are discovered, what they are, a biography of a scientist involved in studying them, a paper about the interplanetary network of satellites and/or the satellites it uses, or some other aspect of GRB research.
- B. Have the students go online and research a recent GRB. Where was it located, what satellite(s) observed it, what else is known about it? They could also write a report on the Gamma-Ray Burst Coordinates Network (or GCN; see <http://gcn.gsfc.nasa.gov/>), which reports new GRBs to the astronomical community.



DO NOT COPY THIS HALF!

Angling for Gamma-Ray Bursts Answer Key

Step 1: Plotting the Satellites and Calculating the Delay Times

- 1) This depends on the scale of the graph paper used. You will need to measure this yourself. The answers given below assume a grid scale of 0.5 centimeters per square.
- 2) 5 minutes; 13 minutes
- 3) 9×10^{10} meters; 2.3×10^{11} meters
- 4) 5 light minutes; 13 light minutes

Step 2: Plotting the Delay Times Using the Light Rulers

- 5) 2.5 cm; 6.5 cm (for 0.5 cm/square)
- 6) 19 minutes 24 seconds

Step 3: Adding a Third Satellite

- 7) 19.4 minutes
- 8) 3.5×10^{11} meters
- 9) 19.4 light minutes
- 10) 9.7 cm (for 0.5 cm/square)

Step 4: Finding the Direction to the Gamma-Ray Burst

- 11) The angle should be close to 17° . Anything within about 5 degrees of this is acceptable.

Reflection Question

- 12) This will depend on the student. Some possible answers include: gamma rays are higher energy, shorter wavelength, and higher frequency than visible light; gamma rays travel at the speed of light, gamma rays and visible light travel in a straight line (unless their path is bent by gravity), gamma rays and visible light from a very distant source travel in parallel lines, gamma rays and visible light can travel in a vacuum, gamma rays and visible light from an object can be used to measure the object's direction.

Math Extension

- 13) $\theta = \arcsin(\text{opposite/hypotenuse}) = \arccos(\text{adjacent/hypotenuse}) = \arctan(\text{opposite/adjacent})$
- 14) The three values should be close to 17°
- 15) The average should be close to 17°
- 16) The *measured* value may be different from the *calculated* value due to measurement errors in the light rulers, or in the angles determined by the light rulers. Let the students use their imagination here.
- 17) From the point-point slope formula:
 $\tan(\text{angle}) = (y_s - y_E) / (x_s - x_E)$
- 18) $\theta_{E-s1} = 63^\circ$ and $\theta_{E-s3} = 135^\circ$

Angling For Gamma-ray Bursts

Student Handout

Introduction

Getting the direction to a GRB in the sky is tricky. The direction to a source that emits optical light is relatively easy to find using aluminum or glass mirrors to focus the light. But gamma rays have such high energies they pass right through glass and aluminum, so a regular lens or mirror is useless. In fact, the original satellites used to discover GRBs could only get a very rough position for them in the sky.

Modern satellites like Swift will be able to get much more accurate directions to GRBs using sophisticated detectors, but for decades this option was not available. What could astronomers do?

An alternative method was cleverly devised using the *timing* of a GRB. Many space probes sent out into the solar system are equipped with detectors that are sensitive to gamma rays. The direction cannot be determined from any given probe, but the exact time of the event can be recorded. When a GRB explodes billions of light years away, the light rays appear to come in as parallel rays to different detectors at widely spaced locations. This fact, together with the timing of the event from different satellites, can be used to determine the direction to the GRB.

In Figure 1 (top), two satellites WIND (S_1) and Swift (S_2) see the light rays from the GRB at different times, since they are at different distances from the burst source. Imagine a plane lying in front of the satellites at some arbitrary distance, perpendicular to the incoming gamma rays. Because the GRB is so far away, the gamma rays arrive at the plane at the same time. They then travel different distances d_1 and d_2 to reach the

satellites. These distances depend on the direction to the burst, as can be seen in Figure 1 (bottom). Light takes a finite time to travel those distances, and the delay between the detection of the burst by the two satellites can be used to determine the direction to the burst.

Note that d_1 and d_2 are parallel. This is because the two satellites see the burst coming from the same direction.

So, if each satellite records the time it receives a burst of gamma rays, then the direction to the GRB can be found knowing the relative positions of the satellites. In fact, since 1990, scientists have used this technique to locate many GRBs on

the sky, using what is called the interplanetary network of satellites (IPN). The member satellites change as old ones are shut down and new ones are added, but in general there are about six satellites in the IPN, and they locate about 150 GRBs per year. Swift itself will be a part of the IPN; although it will directly determine the direction to a GRB, it's always nice to have an independent method as backup.

In this activity, you will determine the direction to a burst using the times it is detected by three different spacecraft located somewhere in the solar system. We are going to assume that all the spacecraft are in the plane of the Earth's orbit around the Sun; that is, there is no third

dimension. We are only concerned with two dimensions, x and y . We will also assume the burst is billions of light years away, so the incoming gamma rays are traveling along parallel lines.

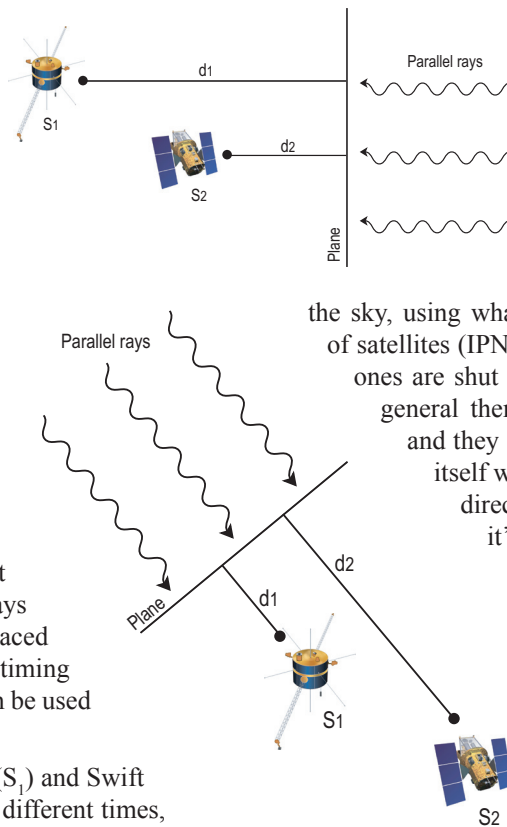


Figure 1

Step 1: Plotting the Satellites and Calculating the Delay Times

You will use your graph paper to represent the Earth's neighborhood in space. Near or at the center of the graph paper, mark one point as the origin (0,0). This will be the location of the Earth. Now draw and label the x and y axes.

Each square on the graph paper will have a length of one **light minute**. A light minute is a measure of distance, defined as the distance light travels in a vacuum in one minute, approximately 1.8×10^{10} meters.

1 light minute =
 1.8×10^{10} meters

1. Using a ruler, measure the length of a row of **ten** squares, then divide by ten to get the length of the side of **one** square in centimeters (cm). Repeat this procedure using different rows of squares, then calculate the average value. Round numbers to the nearest 0.1 cm. If the scale of the grid is given on your graph paper, compare your answer to that. *This number is the scale of the grid in cm/light minutes.*



Using the data listed below, plot the locations of the satellites on the grid. Label the satellites “ S_1 ” and “ S_2 ”. Note that Swift is in low Earth orbit, so on the scale of this grid it is about at the same place as Earth (at 0,0).

On May 16, 2000 at 9:23:00 UT (Universal time, sometimes called Greenwich time), gamma rays from a GRB passed the plane (see Table 1). At 9:28:00 UT satellite S_1 detected the gamma-ray burst. At 9:36:00 UT satellite S_2 detected the same GRB.

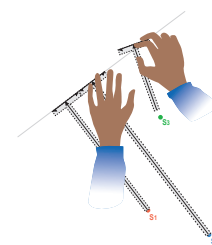
Satellite Name	Satellite Designation	Coordinates (light minutes)
WIND	S_1	(5,10)
Swift	S_2	(0,0)

Table 1

- How long did it take (in minutes) for the light to reach each satellite after it passed the plane?
- Given that the speed of light is 3×10^8 m/s (be careful to note the units!), what distance did the light travel (in meters) to reach the two different satellites after it passed the plane?
- How many light minutes distance did the rays travel after they passed the plane? (Recall that one light minute is about 1.8×10^{10} meters.) Compare your answer to the answer to question 2. What does this imply?

Step 2: Plotting the Delay Times Using the Light Rulers

You have been provided with T-shaped “light rulers,” each of which has a long arrow along the vertical leg, and a shorter arrow along the top crossbar. The crossbar will be considered the “top” of the light ruler, and the other end at the tip of the long vertical leg will be the “bottom.” The arrows are perpendicular, and the long arrow intersects the short one at its middle. These will represent the different distances that light travels from the plane to the two satellites; hence the name “light rulers.” The purpose of these next calculations is to find the lengths for the light rulers.



- Using the grid scale you calculated for Question 1, convert the distances the light traveled in light minutes (Question 2) to centimeters on the graph paper. Round numbers to the nearest 0.1 cm.

Get one of the light rulers. Starting at the tip of the long arrow (where it meets the short one), measure along the long arrow and mark the point on that line such that the length is the length you found in Question 5 for Satellite 1 (see Figure 2). Cut the light ruler at this mark. **Label this ruler S_1 .** Repeat this procedure for the other ruler using the data for S_2 . Don’t forget to label the second ruler! These rulers now represent the distances in grid units that the light traveled from the plane to each satellite.

Now, put the bottom end (the cut end, opposite the long arrow’s head) of each light ruler on the graph so that it is on the position of the satellite it represents. Rotate the rulers around until the short arrows are lined up. It may help to use a straight-edge to line them up. Align them as accurately as you can! The direction that the short arrows point defines the plane, while the long arrows point in the direction to the gamma-ray burst.

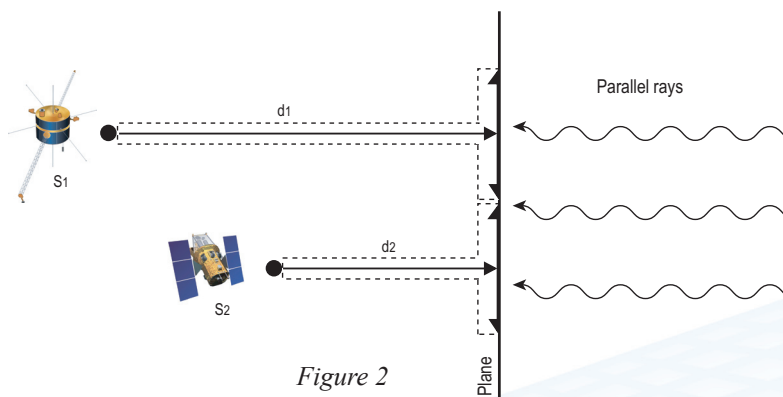


Figure 2

Once the rulers are aligned, lay down your straight-edge over the short arrows on the light rulers and draw the line representing the plane. If you want, you can leave gaps where the light rulers are. Remove the light rulers, then fill in the gaps using your straight-edge. Make sure you extend the line as far as you can on the graph paper. Once you have drawn the line, place the light rulers back on their satellites. Now, starting where you left off before, *continue to rotate the light rulers around*. Is there another position where the two light rulers align as they did before?

When you find another position like the first one, mark it with your straight-edge as you did before. Extend it as far as you can on the graph paper. This line represents a second possible plane, and therefore a second possible direction to the gamma-ray burst. This is a problem: there are two possible solutions to the direction to the gamma-ray burst! We need a tie-breaker, and for that we need to use a third spacecraft.

Step 3: Adding a Third Satellite

We'll use data from the Ulysses spacecraft and proceed as before with S_1 and S_2 . Use the table below to add Ulysses to your graph. Call it S_3 .

On May 6, 2000, at 9:42:24 UT, satellite S_3 detected the same GRB as the other two spacecraft did.

Satellite Name	Satellite Designation	Coordinates (light minutes)
Ulysses	S3	(-10, 10)

Table 2

- How long did it take (in minutes and seconds) for the light to reach satellite S_3 after it passed the parallel plane?
- Convert to decimal minutes (for example, 1 minute 30 seconds = 1.5 minutes).
- What distance (in meters) did the light travel to reach the satellite S_3 after it passed the plane?
- How many light minutes distance did the rays travel after they passed the plane?
- Use the grid scale to convert this distance to centimeters on the graph.

Step 4: Finding the Direction to the Gamma-Ray Burst

As you did before, measure, mark, and cut the third light ruler so that its length represents the light travel distance you found in Question 9. Place the bottom of the light ruler on S_3 , and rotate it around. You should find that the short arrow aligns with only one of the two lines representing possible planes. Label this line as the correct one. That's the plane that is perpendicular to the direction of the GRB.

However, simply knowing the direction isn't good enough; astronomers will want a number representing the angle from the Earth to the gamma-ray burst. You'll need to measure that angle with a protractor. First, find a perpendicular line that connects the Earth to the plane. Hint: you have already done this with the light ruler! Draw the line.

- Assuming the x-axis represents 0° and that the angle increases counter-clockwise, measure the angle from the x-axis to the line connecting the Earth and the plane.

Congratulations! Now astronomers back on Earth will know where to point their telescopes to follow-up on this burst.

Reflection Question

- Explain at least two properties of gamma-ray light (for example, how it is different or similar to visible light?).

Math Extension (optional, for geometry and trigonometry students):

In reality, astronomers won't draw the lines and use a protractor. They use trigonometry to determine the angle. To determine the angle, first make sure the line representing the plane is extended so that it intersects the x-axis of your graph. You now have a right triangle, with one side whose length you have already calculated. From this, you can find the angle from the Earth to the GRB as measured from the x-axis.

- Write down trigonometric formulae that show how to compute the value of the angle using sines, cosines, and tangents of the lengths of the different sides of the triangle.
- Using each of those trigonometric formulae, calculate the value of the angle from the Earth to the gamma-ray burst in degrees.
- Average the three angles to get a predicted direction to the gamma-ray burst.
- Compare this value to what you measured in question 11, and comment on any differences if there are any.
- Write down a **general equation** for the angle from the Earth to satellites S_1 and S_3 with respect to the x-axis (Satellite 2, Swift, is orbiting the Earth so we have assumed it is at Earth's position.)
- Calculate the value of the two angles.

Angling For Gamma-ray Bursts

Student worksheet

NAME _____

DATE _____

Step 1: Plotting the Satellites and Calculating the Delay Times

1. a) Length of one square (1st measurement)
_____ (cm)
- b) Length of one square (2nd measurement)
_____ (cm)
- c) Average of two measurements
_____ (cm)
2. t_{s1} = _____ minutes
 t_{s2} = _____ minutes
3. d_{s1} = _____ meters
 d_{s2} = _____ meters
4. d_{s1} = _____ light minutes
 d_{s2} = _____ light minutes



Make sure you
check your
units!

Step 2: Plotting the Delay Times Using the Light Rulers

5. d_{s1} = _____ cm on the graph
 d_{s2} = _____ cm on the graph

Step 3: Adding a Third Satellite

6. t_{s3} = _____ minutes _____ seconds
7. t_{s3} = _____ minutes
8. d_{s3} = _____ meters
9. d_{s3} = _____ light minutes
10. d_{s3} = _____ cm on the graph

Step 4: Finding the Direction to the Gamma-Ray Burst

11. Angle from the x-axis to the gamma-ray burst
_____ (degrees)

Reflection Question

12. Use the space below and/or the back of this sheet to write your answer.

Math Extension:

13. Formulae for angle:

$\sin \theta$ = _____

$\cos \theta$ = _____

$\tan \theta$ = _____

14. Direction to the gamma-ray burst

using $\sin \theta$ formula _____ (degrees)

using $\cos \theta$ formula _____ (degrees)

using $\tan \theta$ formula _____ (degrees)

15. Average of three numbers _____ (degrees)

16. Use the space below and/or the back of this sheet to write your answer.

17. Equation for angle = _____

18. θ_{s1} = _____ degrees

θ_{s3} = _____ degrees