Distance Measurement Methods

A. Parallax from Images

In this exercise, you will determine the distances to stars that appear in a pair of images taken 3 months apart. Some stars are in different positions in the two images. You will also determine the minimum distance to those stars for which there is no measurable parallax.

Take a look at the two star field images. You can assume that the patch of sky in these images is near the plane of the ecliptic. (Note that these images are actually artificial constructions to make it possible to measure many stellar parallaxes in one image. In reality, stars that are close enough to us to have measurable parallaxes wouldn’t be so close together on the sky.) The images are “negatives,” so that stars appear black on a white background. The size of a star in the images is determined not by the star’s physical dimensions, but by its brightness. The brighter stars appear bigger than faint ones.

Step 1: Compare the two star images carefully, looking for stars that appear in different locations in the two images. You may find it helpful to lay image #1 on top of image #2, and hold them up to a light. Be careful to align the two images well (most stars will line up perfectly). You can also try using a ruler to check if separations or alignments between stars have changed.

Step 2: Mark each star that has moved noticeably with an arrow on image #1. Draw the arrows in BELOW the stars, so they point “up” at the stars. Label each star with a number, letter or name.

Step 3: For each star that moves, estimate its center by eye as best you can on image #1, and make a small dot there with a pen or pencil. Then lay image #1 on top of image #2, and look for where each star moved to in image #2. Make a small dot on image #1 at the location where the star is centered in image #2. You should now have two dots on image #1 associated with each star that moves.

Step 4: Use a ruler to measure how far each star has shifted in the three-month period between image #1 and image #2. Make the measurements in millimeters (mm), and record each measurement in the second column of Table 1 on your worksheet.

Step 5: Convert your measurements in millimeters to an angular size using the following conversion:

\[ 1 \text{ mm} = 0.1 \text{ arc-second} \]

The resulting shift in units of arc-seconds is the known as the “parallax” of the star. Record the parallax values in the third column of Table 1.
**Step 6:** Compute the distances to each of the stars that moved noticeably. Use the parallax formula:

\[ d = \frac{1}{p} \]

Here \( d \) is the distance in parsecs (pc) and \( p \) is the parallax angle measured in arc-seconds. For example, a star with a parallax of 0.5 arcsec has a distance of \( \frac{1}{0.5} = 2.0 \) pc. Record your results in the fourth column of Table 1.

**Step 7:** Compute the distances to each of the stars in light years (ly), and record your results in Table 1. Use the conversion:

\[ 1 \text{ pc} = 3.26 \text{ ly} \]

**Step 8:** Estimate the smallest apparent shift you hypothetically could have measured. That is, how far in mm would a star need to have shifted for you to be able to notice the shift? What does this smallest measurable shift correspond to in arc-seconds? Then compute the distance to a star that has this value of the parallax, following steps 5 and 6 above. Record your answers on the worksheet, and answer the following questions.

**Q1:** Look at your results from Step 6 (distance column in Table 1) above. What, if anything, can be said about the distances of stars that didn’t seem to move from image #1 to image #2? [For example, “they must be closer than....” or “they must be farther away than....” Fill in the blank with a number.]

**Q2:** Suppose you observed the same field of stars 3 months after image #2 was taken. Describe in words how you would expect the positions of stars to appear. Include a sketch if that would help explain what you would see.

**Q3:** Suppose you observed the field once more 9 months after image #2 was taken. Describe in words how you would expect the apparent positions of stars to compare to those observed in image #1 and/or image #2.

**Q4:** Put aside the images you’ve been working on for a moment. Imagine that all the stars in the galaxy have the same intrinsic brightness, like light bulbs all of the same wattage. Stars would then appear brighter or fainter depending on whether they were relatively close or relatively far away from the Earth. If this were the case, which stars would appear brighter as seen from Earth: those with large parallaxes, or those with small parallaxes? Explain.

**Q5:** Now consider the results of your analysis of the two images. Are the results consistent with the hypothesis that all stars in the Galaxy have the same intrinsic brightness? Why or why not? If not, give at least one specific example from this exercise that proves your point.
B. Other Distance Measures
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This exercise demonstrates three of the major distance measuring techniques: radar, parallax, and "standard candles" (both linear size and luminosity). Answer questions on the following worksheet.

Background

One of the most difficult problems in astronomy is determining the distances to objects in the sky. There are four basic methods of determining distances: radar, parallax, standard candles, and the Hubble Law. Each of these methods is most useful at certain distances, with radar being useful nearby, and the Hubble Law being useful at the most distant scales. This exercise will focus on how radar and standard candles are used.

Part 1: Radar

Using radar to measure the distance to an object is fairly straightforward, and much like using an echo. Dolphins find their way around underwater in this way, and you might judge the sizes of large, dark rooms this way. We are going to simulate radar using a person for the pulse of light.

In astronomy, a radio telescope is used for the radar dish (the Aricebo Radio Telescope, for example). The radar pulse travels at the speed of light, and much larger distances are involved, such as the distance to Mercury.

Step 1: Find a place outside or along a hallway where you can walk freely. Both partners should begin at the same location.

Step 2: One of you will be the radar pulse, and the other will be the scientist on Earth. Radar works because we know the speed at which light travels. Because your "radar pulse" will not travel at the speed of light, you need to find the actual speed of the "radar pulse". The "radar pulse" should walk at an even, repeatable speed, and the scientist should measure how far the pulse travels in 5 seconds. Calculate the speed of travel from the distance and the time. Record your measurements and calculations on the worksheet.
**Step 3:** Now pick an object that you would like to measure the distance to. The scientist gives the signal to begin, and the radar pulse begins to travel toward the object (trying to walk at the same speed as in Step 2). The scientist times the "radar pulse's" trip (both going to the object and returning). When the pulse comes to the object, it "bounces" off, and travels back in the direction it came. The number of seconds elapsed is the total time, t, taken for the pulse to travel out, bounce off the object, and travel back again.

**Step 4:** The distance to the object, d, is given by the following formula where "s" is the speed of the pulse (measured on Step 2), and "t" is the total travel time of the pulse to the object and back (recorded in Step 3).

\[ d = s \cdot \left( \frac{t}{2} \right) \]

This equation may be more familiar to you if worded this way: the distance traveled is equal to the speed multiplied by the time it took to get there. So if you are traveling at 60 mph for one hour, you've traveled 60 miles. Calculate the distance to the object using the speed from Step 2, and record your results on the worksheet.

When astronomers use radar, they are typically using a pulse of light, which travels at the speed of light: (about 186,000 miles per second). Neptune is about \(2.5 \times 10^9\) miles away from Earth (on average), and the nearest star beside the Sun, Proxima Centauri, is about \(2.5 \times 10^{13}\) miles away.

**Q6:** How long would it take a radar pulse going at the speed of light to travel to Neptune and back?

**Q7:** How long would it take a radar pulse going at the speed of light to travel to the Proxima Centauri and back?

**Q8:** Given your answers to the previous two questions, what would you estimate is the most effective range of distances to measure using radar?

**Part 2: Standard Candles**

**Step 1:** The first sort of standard candle is uniform in size (the second sort is uniform in brightness, but we will deal more with those later). When you look down from the top of a skyscraper, you don't say to yourself "Look at all those tiny people!" You say, "Look how far I am from those regular-sized people!" Okay, maybe you don't talk to yourself, but we don't think the people actually shrink. In a similar way, we can take astronomical objects of all the same type, and find their distance by how small they appear in the sky.

Record your height and that of your lab partner in the chart on the worksheet.
**Step 2:** Now you need a measuring tool for angles. But you already have one that you carry with you all the time! The width of your palm (including your thumb) when held at arm's length measures about 10 degrees on the sky, and the width of your finger at arm's length measures about 2 degrees. Have your lab partner pace off a distance outside (at least 5 feet), and stand there. Measure and record the distance in the data table. Measure your partner’s height in degrees, and have them measure yours. Now move further apart, and record the distance in the data table. Again, measure their height in degrees and have them measure yours. Do this three times more (for a total of five measurements). Record your results in the table, and answer the following questions.

**Q9:** What is the trend in the above angular height measurements, qualitatively?

**Q10:** Did the actual heights change at all during this experiment?

**Q11:** Suppose that you had a friend the same height as your lab partner. If you see them on the street, can you figure out how far away they are using this method? Why or why not?

**Q12:** Galaxies, like stars, come in a large range of sizes. Would this technique work for estimating the distances to galaxies? Why or why not?

**Step 3:** Now plot your data on graph paper, so that the distance between the two of you is on the x-axis, and angular size is on the y-axis. Use a different color or symbol for your own height and that of your lab partner.

**Q13:** Are the points random, or is there a relationship between them? If so, describe the relationship.

**Q14:** How reliable is this method for determining distances? Explain.

**Q15:** Suppose you used 5 different people at 5 different distances. How would this change your results? How does this relate to the astronomical situation?
### TABLE 1: Stars with Measurable Parallaxes

<table>
<thead>
<tr>
<th>Star name</th>
<th>Amount of shift (mm)</th>
<th>Parallax (Arcsec)</th>
<th>Distance (parsecs)</th>
<th>Distance (Light-years)</th>
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**Step 8:**

- Smallest possible measurable shift: ________ mm
- Smallest possible measurable parallax: ________ arcsec
- Distance to star for which a parallax could just barely be measured: ________ pc

### Radar Data

- Distance pulse traveled in 5 seconds= ________________
- Speed of the radar pulse (s)= ________________
- Length of time for pulse to return to scientist from distant object (t)= ________________
- Calculated distance (d)= ________________
### Part 2: Standard Candles

Actual height, You: ________________ Lab Partner: ________________

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<th></th>
<th>Distance</th>
<th>Angular Height: You</th>
<th>Angular Height: Lab Partner</th>
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