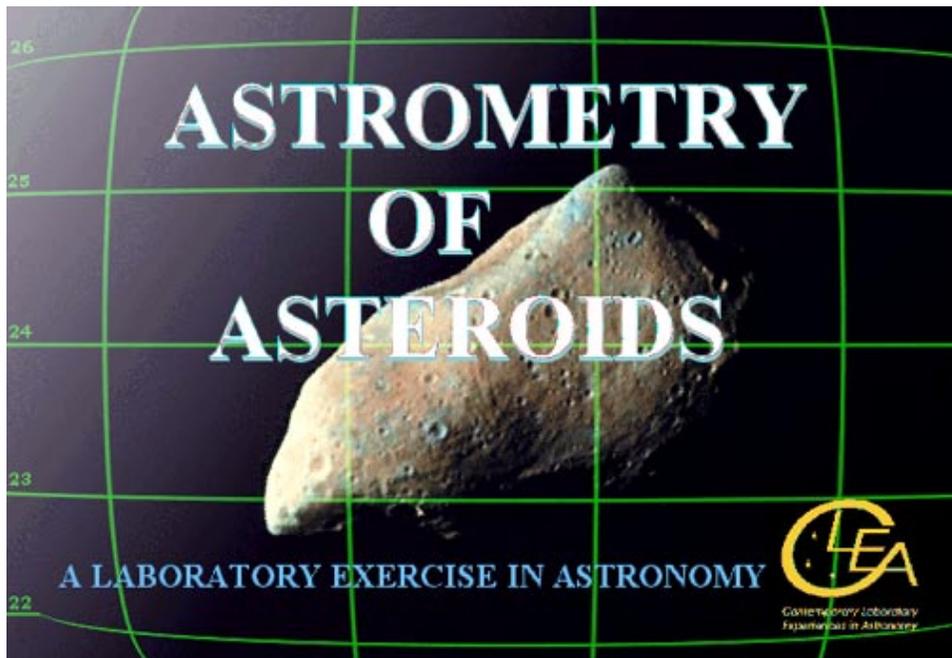


Astrometry of Asteroids

Student Manual

A Manual to Accompany Software for
the Introductory Astronomy Lab Exercise
Document SM 9: Version 0.70 lab



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Contemporary Laboratory
Experiences in Astronomy

Contents

Goals	3
Objectives	3
Introduction	4
Astrometrical Coordinate systems and the Technique of Astrometry	4
The Notion of an Astronomical Coordinate System	4
The Equatorial Coordinate System: Declination and Right Ascension	5
The Technique of Astrometry: Finding the Coordinates of Unknown Objects	6
The Problem of Finding Asteroids	7
The Principles of Parallax	8
Equipment	9
Operating the Computer Program	9
Overall Strategy	9
Starting the program	9
Accessing the HELP Files	9
Part I	10
Finding Asteroids by Blinking Images	10
Procedure for Part I	10
Part II	14
Measuring the Equatorial Coordinates of an Asteroid by Comparing It to Positions of Known Stars in the Hubble Guide Star Catalog	14
Procedure for Part II	14
Part III	19
The Angular Velocity of Asteroid 1992JB	19
Procedure for Part III	19
Part IV	23
Measuring the Distance of Asteroid 1992JB by Parallax:	23
Procedure for Part IV	24
Part V: The Tangential Velocity of Asteroid 1992 JB	27
Optional Questions and Activities	28
QUESTION 1	28
Optional Activity	29
References	30

Goals

You should be able to understand how moving objects can be discovered on images of the sky.

You should understand the fundamentals of how the equatorial coordinate system, right ascension, and declination, can be used to locate objects on the sky.

You should understand how reference stars of known coordinates can be used to interpolate the coordinates of unknown objects.

You should appreciate the way in which astronomers measure parallax and use it to determine the distance to objects in the solar system and beyond the solar system.

Objectives

If you learn to.....

Display CCD images of the heavens using an astronomical image display program.

Blink pairs of images, and learn to recognize objects that have moved from one image to the next.

Call up reference star charts from the Hubble Guide Star Catalog (GSC) stored on the computer.

Recognize and match star patterns on the GSC charts against the stars in your image

Measure the coordinates of unknown objects on your images using the GSC reference stars.

You should be able to.....

Find asteroids on pairs of CCD images.

Measure the angular velocity of the asteroid in arcseconds per second.

Measure the parallax of an asteroid seen from two sites on opposite sides of the US.

Use the parallax to determine the distance of an asteroid, using the same technique astronomers use to measure the distance of stars.

Use the distance of the asteroid and its angular velocity to determine its tangential velocity.

Useful Terms You Should Review in Your Textbook

<i>Angular velocity</i>	<i>AU</i>	<i>Degrees</i>	<i>Parallax</i>	<i>Universal Time</i>	<i>Minutes</i>
<i>arcminutes</i>	<i>Blinking</i>	<i>Hours</i>	<i>Proper Motion</i>	<i>arcseconds</i>	<i>Seconds</i>
<i>Asteroids</i>	<i>Coordinates</i>	<i>Magnitude</i>	<i>Right Ascension</i>	<i>Declination</i>	

Introduction

Astrometrical Coordinate systems and the Technique of Astrometry

The techniques you will be using for this lab involve the measurement of precise star positions, a technique called astrometry, which is one of the fundamental tools of astronomers. Astrometry, of course, enables us to make charts of objects in the sky, assigning two numbers or celestial coordinates to each object so that we can easily locate it. If you've ever used a roadmap or a map of the world, where two coordinates are used to mark the positions of cities and mountains, you know the usefulness of coordinate systems.

Astrometry also helps astronomers measure the changes in positions of objects in the heavens. One of these changes, called annual parallax, enables astronomers to measure the distances to stars. Parallax is a semi-annual change in the position of a star caused by changing perspective as the earth circles the sun. Another change, called the proper motion of a star, is a uniform drift across the sky caused by the motion of the star itself with respect to us.

By using computers to measure the positions of stars on digital images of the sky, astronomers determine the coordinates of objects to high precision. Even the relatively simple program you will be using in this exercise can pinpoint objects to better than 0.1 arcseconds, which is about the diameter of a dime viewed from a distance of 20 kilometers. This is not high enough precision to measure the parallax of most stars because most stars are too far away, and therefore have a very small annual parallax. So we have chosen to demonstrate astrometric measurement using asteroids, those small rocky planets that orbit the sun—most of them between the orbit of Mars and Jupiter. You will be able to measure the parallax and the motion of asteroids quite easily, and the techniques you learn here are applicable both to asteroid work and to the study of the positions and motions of the stars.

The Notion of an Astronomical Coordinate System

How do astronomers know where a star is in the sky? They use the same method we use here on earth to specify the position of a city on the globe or a street on a map of the city: they give two numbers, called the coordinates of the star, that enable us to pinpoint the object. Imagine the sky covered with a grid of imaginary lines, labeled with numbers. To say that a star is at (X,Y) in the sky, is just like saying a city is at longitude 77 west, latitude 140 north, or that a street is at L, 5 on a map. To find the city, you just look to see where the longitude line labeled "77 west" intersects with the latitude line labeled "40 north", and there it is. To find the street, you just look to see where line L intersects line 5 on the map. Two coordinates are all that is needed since the surface of the earth, the city map, and the sky, all appear two dimensional to the observer.

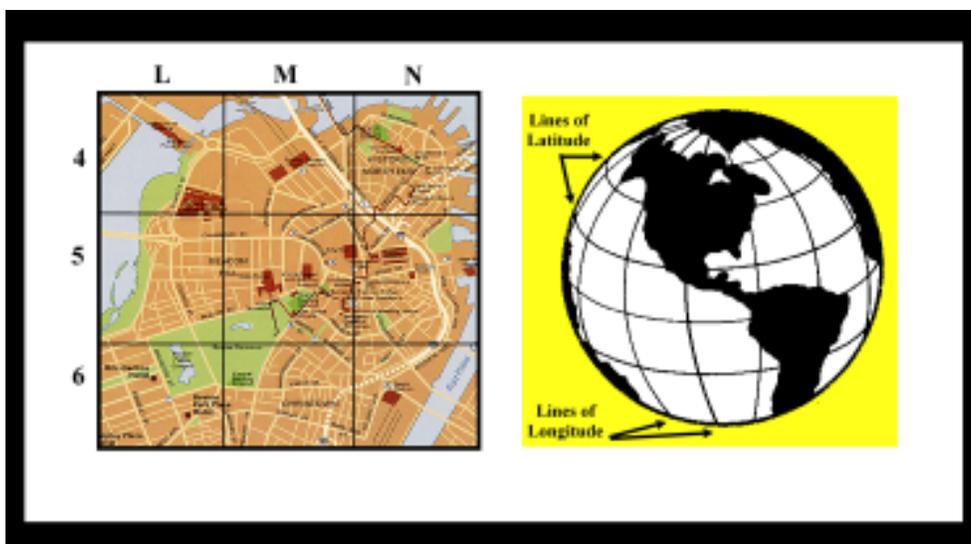


Figure 1
Coordinate Systems

The Equatorial Coordinate System: Declination and Right Ascension

Positions are always measured with respect to something. For instance, latitude and longitude are measured with respect to the earth's equator and the Greenwich meridian. Coordinates on a piece of graph paper are measured with respect to the corner or to the origin of the graphs. The coordinates that are commonly used to specify star positions in astronomy indicate the star's position with respect to the celestial equator, an imaginary line in the sky that runs above the earth's equator, and are therefore called the equatorial coordinate system. The two coordinates in the equatorial system are called Declination and Right Ascension.

The lines of declination are like lines of latitude on the earth, and are designated by their angular distance north or south of the celestial equator, measured in degrees ($^{\circ}$), arcminutes ($'$), and arcseconds ($''$). There are 360 degrees in a circle, 60 minutes in a degree, and 60 seconds in a minute. A star with a declination of $+45^{\circ} 30'$ lies 45 degrees, 30 minutes north of the celestial equator; negative declinations are used for an object south of the equator.

Right ascension lines are like lines of longitude on the earth, running through the north and south celestial poles perpendicular to the lines of declination. They designate angular distance east of a line through the vernal equinox, the position of the sun when it crosses the celestial equator on the first day of spring. Right ascension is measured in hours ($^{\text{h}}$), minutes ($^{\text{m}}$) and seconds ($^{\text{s}}$). This may sound strange, but an hour of right ascension is defined as $1/24$ of a circle, so an hour of right ascension is equal to 15 degrees. There are 60 minutes in an hour, and 60 seconds in a minute of right ascension. A star with a right ascension of 5 hours would be 5 hours, or 75 degrees, east of the line of right ascension (0^{h}) that runs through the vernal equinox.

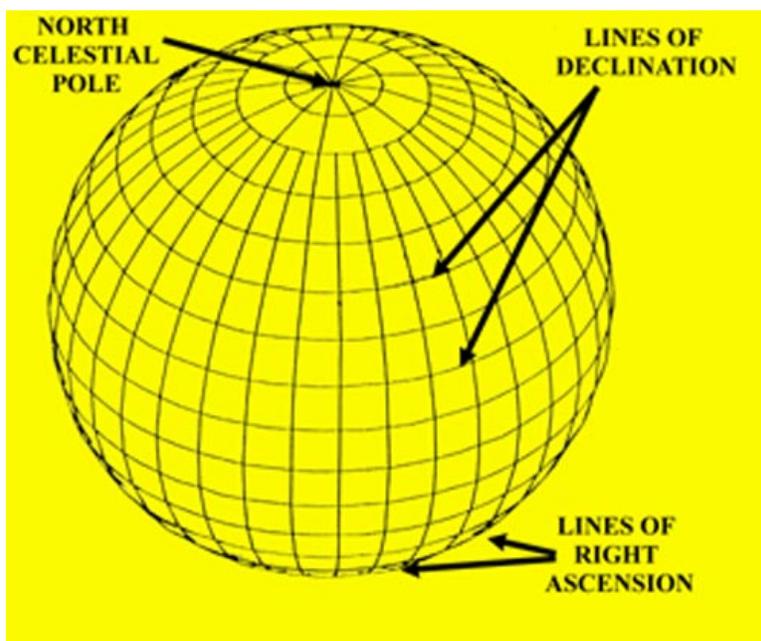


Figure 2
The Equatorial Coordinates

There are many catalogs of objects in the heavens which list their right ascensions and declinations. It's impossible to list all the stars in the sky, so a catalog usually contains stars that are selected by astronomers for a particular purpose. One of the most important catalogs is called the *FK5 Catalog*, because it is one of the fundamental catalogs used as a reference for measuring the positions to other stars in the sky (see the next section of this manual). The *FK5 Catalog* only contains 3522 stars, all of them rather bright. The right ascensions and declinations of the stars in the *FK5 Catalog* have been especially carefully measured and re-measured so that they can be relied upon as standard reference points for the measurement of the positions of other objects in the sky.

Another useful catalog which we shall use in this exercise is the *Hubble Space Telescope Guide Star Catalog*, (*GSC*).

The *GSC* lists almost all the stars in the sky that are brighter than apparent magnitude 16, which is almost ten thousand times fainter than the faintest star you can see with your naked eye. There are coordinates of almost 20 million stars in the *GSC*, so many that the full catalog requires two CD-ROMs to hold it. The *GSC* has been one of the most useful catalogs for astronomers in recent years. There are so many stars in it, scattered all over the sky, that you can practically count on having several *GSC* stars with known coordinates anywhere you look in the sky. On the other hand, there are so few stars in the *FK5 Catalog*, that it's rare that a *FK5* star will be in the same direction as an object of interest.

In this exercise, you'll only be looking at a few specific spots in the sky. To save room on your computer, we've extracted only part of the GSC and stored it on your computer for use in this exercise.

The Technique of Astrometry: Finding the Coordinates of Unknown Objects

The lines of right ascension and declination are imaginary lines of course. If there's an object in the sky whose right ascension and declination aren't known (because it isn't in a catalog, or because it's moving from night to night like a planet), how do we find its coordinates? The answer is that we take a picture of the unknown object, U, and surrounding stars, and then interpolate its position of other nearby stars A, and B, whose equatorial coordinates are known. The stars of known position are called reference stars or standard stars.

Suppose, for instance, that our unknown object lay exactly halfway between star A and star B. Star A is listed in the catalog at right ascension 5 hours 0 minutes 0 seconds, declination 10 degrees 0 minutes 0 seconds. Star B is listed in the catalog at right ascension 6 hours 0 minutes 0 seconds, declination 25 degrees 0 minutes 0 seconds. We measure the pixel positions of stars A and star B and U on the screen and find that U is exactly halfway between A and B in both right ascension (the x direction) and declination (the y direction). (See Figure 3 below).

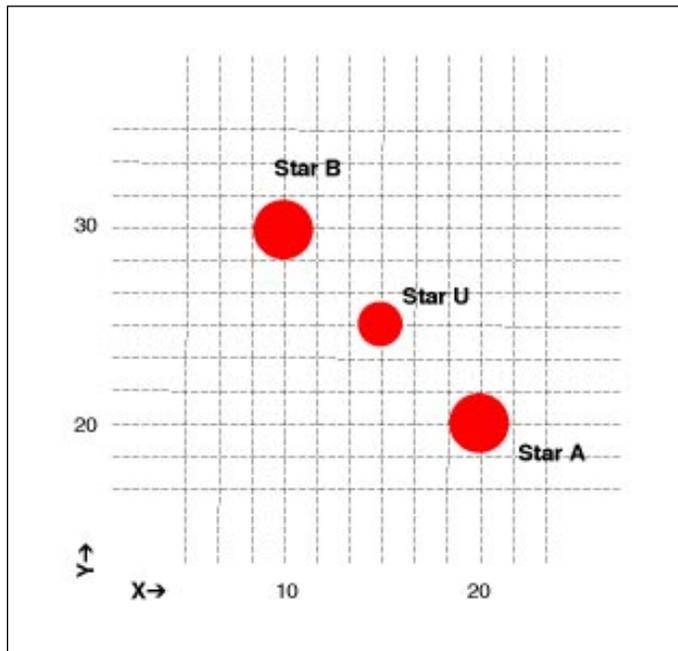


Figure 3
Determining the Coordinates
of an Unknown Object

We can then conclude that the right ascension of the unknown object is halfway between that of A and B, or 5 hours 30 minutes 0 seconds; and the declination of the unknown object is halfway between that of A and B, or 17 degrees 30 minutes 0 seconds. This is outlined in the table below.

If the unknown object isn't exactly half-way between the two known stars, the interpolation is a bit more complicated. In fact, in practice it's a bit more involved largely because the image of the sky appears flat and, in actuality, the real sky is curved. But it is not difficult to write easy to use software that will do the mathematics for you, and the program we supply does just that. To measure a unknown object's position from an image, the software will instruct you to choose at least three stars of known coordinates (for best results choose more). Then indicate the location of the unknown object by clicking on it. The computer performs what is called a coordinate transformation from the images on the screen to the equatorial coordinates, and prints out a solution showing you the coordinates of your unknown object. The software we

provide can, in principle, calculate coordinates with a precision of about 0.1 seconds of an arc. That's approximately the angular diameter of a dime seen at distance of about 20 miles, a very small angle indeed.

Star	Right Ascension	Declination	X Position on Image	Y Position on Image
Star A	5h0m0s	10°0'0"	20	20
Star B	6h0m0s	25°0'0"	10	30
Unknown Star U	?	?	15	25

The Problem of Finding Asteroids

In this exercise you will be using images of the sky to find asteroids and measure their positions. Asteroids are small rocky objects that orbit the sun just like planets. They are located predominately between the orbit of Mars and Jupiter, about 2.8 Astronomical Units from the sun. Asteroids do orbit closer to the sun, even crossing the earth's orbit. Occasionally an earth-crossing orbit, may even collide with the earth. Hollywood movie producers have frequently used an asteroid collision as a plot for a disaster movie. The danger is real, but dangerous collisions are very infrequent.

Most asteroids are only a few kilometers in size, often even less. Like the planets, they reflect sunlight, but because they are so small, they appear as points of light on images of the sky. How then can we tell which point of light on an image is an asteroid, and which points are stars?

The key to recognizing asteroids is to note that asteroids move noticeably against the background of the stars because an asteroid is orbiting the sun. If you take two pictures of the sky a few minutes apart, the stars will *not* have moved with respect to one another, but an asteroid will have moved. (See figure 4).

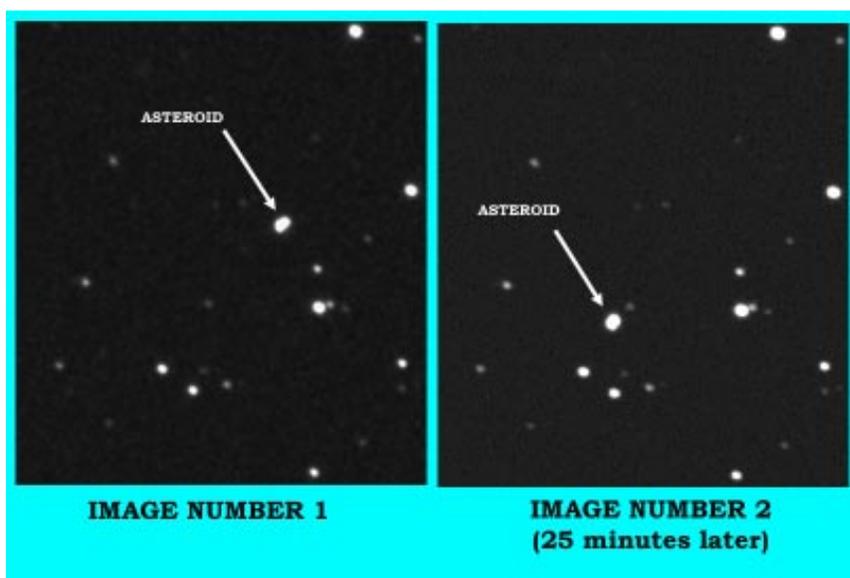


Figure 4
Finding the Asteroid

It's hard to see the forest for the trees, however. Often there are so many stars on a picture that you can't easily remember the pattern when you look at another image, and therefore you can't easily tell which dot of light has moved. Computers come to the rescue again! You can load and display simultaneously two images of the sky that were previously taken with a telescope. You then instruct the computer to switch the display quickly back and forth from one image to another, a technique called blinking. If you are careful to line up the stars on the first image with the stars on the second image *before* you blink the two images, the only object that will change will be the

asteroid, which will appear to jump, making it easy to spot. Our computer program enables you to easily align the stars on two images and then blink back and forth, making asteroids jump to your attention.

Sometimes the asteroids will be faint; other times there will be spots or defects that appear on one image and not on another. These spots can mislead you into thinking that something has moved into the second image that was not there in the first. So even with the ease of blinking, you should carefully inspect the images, in order to pick out the object (or objects) that really move from a position on the first image to a new position on the second.

Once you've identified an asteroid on a picture, you can then get the computer to calculate its coordinates by measuring its position with respect to reference stars (stars of known coordinates) on the screen. Comparing an asteroid's position at particular time with its position at some other time enables you to calculate the velocity of the asteroid, as we will see later in this exercise.

The Principles of Parallax

Measurement of precise positions are key to one of the most powerful methods astronomers have of measuring the distances to objects in the sky, a method known as parallax. Parallax is the most direct way astronomers have of measuring the distances to stars.

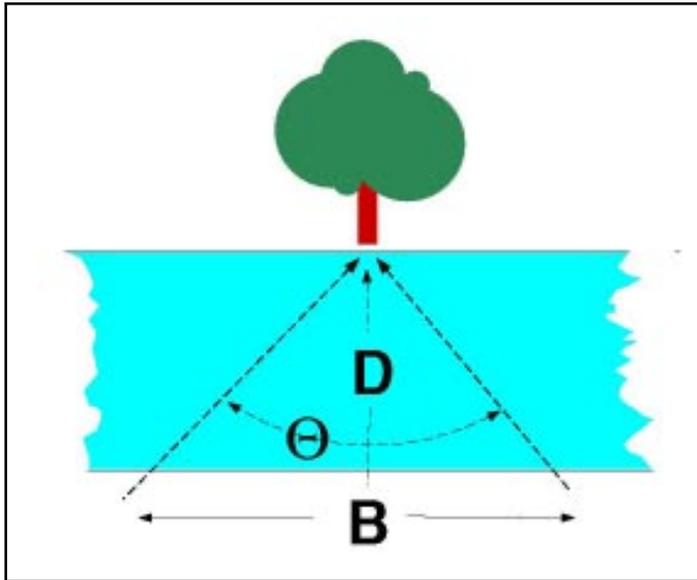


Figure 5
Parallax of an Object

The parallax of an object is its apparent shift in position when you view the object from two different vantage points. It's commonly used on the earth to measure the distance across a wide river (see Figure 5 below). You view a tree from two vantage points on the opposite shore. You carefully measure the distance between the two vantage points, called the baseline, **B**, and the angle between the two lines of sight to the tree, parallax angle designated as Θ . Using trigonometry, you can find the perpendicular distance across the river. Since the distance, **D**, is one side of a right triangle, the opposite angle of which is $\Theta/2$, and the adjacent side of which is **B/2**, the distance across the river can be represented as

$$D = \frac{B/2}{\tan(\Theta/2)}$$

In general, if you can measure the parallax, Θ , of an object as measured from two points separated by a baseline, **B**, you can measure its distance.

In astronomy, a commonly used baseline is the diameter of the earth's orbit and the parallax we measure is due to the shift in vantage point as the earth orbits the sun. If we view a nearby star from opposite sides of the earth's orbit, and measure its position against a background of distant stars, we will see that it appears to move. For example, its equatorial coordinates measured in June, when the earth is at one side of the sun, will be different from its position in January when the earth is at the other side of the sun (see Figure 5). The further the star, the smaller the parallax. Even the nearest stars have parallax shifts of less than a second of an arc, hard to see and hard to measure. However, astronomers have been able to measure the parallaxes of over a hundred thousand stars using sophisticated techniques and a special satellite called Hipparchos.

It is also possible to measure the distance to asteroids using parallax too. Because asteroids are closer, their parallax is larger, and we can even use a short baseline - like the diameter of the earth. Viewed from two points on the earth, asteroids show a very noticeable parallax, as you will see in Part IV of this exercise. Measuring the parallax of asteroids using astrometry is a useful exercise for showing us how the much smaller parallax of stars is measured in practice.

Equipment

You will need a scientific pocket calculator, graph paper, ruler, PC compatible computer running Windows 3.1 (VGA graphics) or Win95, and the CLEA Program *Astrometry of Asteroids*.

Share the use of the computer and program with your partner to collect data. All calculations and graphing, as well as your narratives, must be your own original work.

Operating the Computer Program

Overall Strategy

1. Login and enter student information.
2. Access and browse through the Help Screens.
3. Become familiar with the procedure of loading and displaying CCD images, and learn how to blink images in order to identify which object is the asteroid.
4. Using the GSC and the technique of blinking the image, you will measure the equatorial coordinates of the asteroid.
5. Determine how fast the asteroid is moving and its distance from earth by using the data you have collected on the asteroid's position in conjunction with simple trigonometric formulae.

Starting the program

Your computer should be turned on and running Windows. Your instructor will tell you how to find the icon or menu bar for starting the *Astrometry of Asteroids* exercise. Position the mouse over the program's icon or menu bar and click to start the program. When the program starts, the CLEA logo should appear in a window on your screen. Go to the File menu bar item at the top of that window, click on it, and select the Login option from the menu. Fill in the form that appears with your name (and partner's name, if applicable). Do not use punctuation marks. Press tab after each name is entered, or click in each student block to enter the next name. Enter the Laboratory table number or letter if it is not already filled in for you. You can change and edit your entries by clicking in the appropriate field and making your changes. When all the information has been entered to your satisfaction, click OK to continue, and click yes when asked if you are finished logging in. The opening screen of the *Astrometry of Asteroids* lab will then appear.

Accessing the HELP Files

You may, at any time, select **Help** from the menu to receive on-line help. Click **Help** located on the right hand side of the menu bar. Within **Help...Topics**, there are five options that you can select: **Login, Files, Images, Reports,** and **Close the Program**. **LogIn** informs you of the initial steps required to begin the program. **Files** provides information on the types of files used in this exercise and how to load these images. **Images** explains how to retrieve and modify images, print images, blink images, and measure images. Using the **Help...Topic...Reports** menu choice will show you how you can review your observational data and also how to compute projected baselines. **Close the Program** gives the procedure on how to exit the program as well as a reminder of any unsaved data. There is no user help for this program therefore **User** is disabled. **About This Exercise** displays the title and version number of the program as well as the copyright information.

Part 1

Finding Asteroids by Blinking Images

On your computer you will find a series of images of a region of the sky, about 4 arcminutes square, in which astronomers were searching for a faint earth-approaching asteroid designated 1992JB. The problem is to recognize the asteroid, which as the name suggests (asteroid = “starlike”), looks just like a star. How can we distinguish between one type of object and another?

The answer is that asteroids appear to move, while stars do not. In the first part of this exercise you will examine the images to find a moving object, the asteroid 1992JB. The technique you will use is called *blinking*. Using 2 stars on each image as reference points, you can align the images electronically in the computer. After alignment, whenever you turn on the blink feature, the computer will quickly switch its display from one image to another. Stationary objects like stars will not appear to change position, but objects that have moved from one image to the next will appear to jump, drawing your attention to them. You can thus identify which starlike object is, in fact, the asteroid.

Procedure for Part I

1. Let's look at one of the images. From the menu bar, choose **File...Load...Image 1**. A directory listing showing you a list of files appears. From this list, select 92jb05.fts, and click **Open** to load it.
 - The computer will show you the progress of the loading and creating a screen for display and then write the name of the file on the screen to let you know it has successfully loaded Image 1. The program can load two files, **Image 1** and **Image 2** for blinking purposes.
 - The image has been loaded, but is not yet displayed. To display it, select **Images** on the menu bar, then choose **Display...Image 1** from the pull-down menu. A window showing the image 92JB05 will appear on your screen. (The display window containing the image uses the same window control symbols found in any Windows program. Using the “-” button at the upper right minimizes the window, and using the “x” button at the upper right removes the window.)

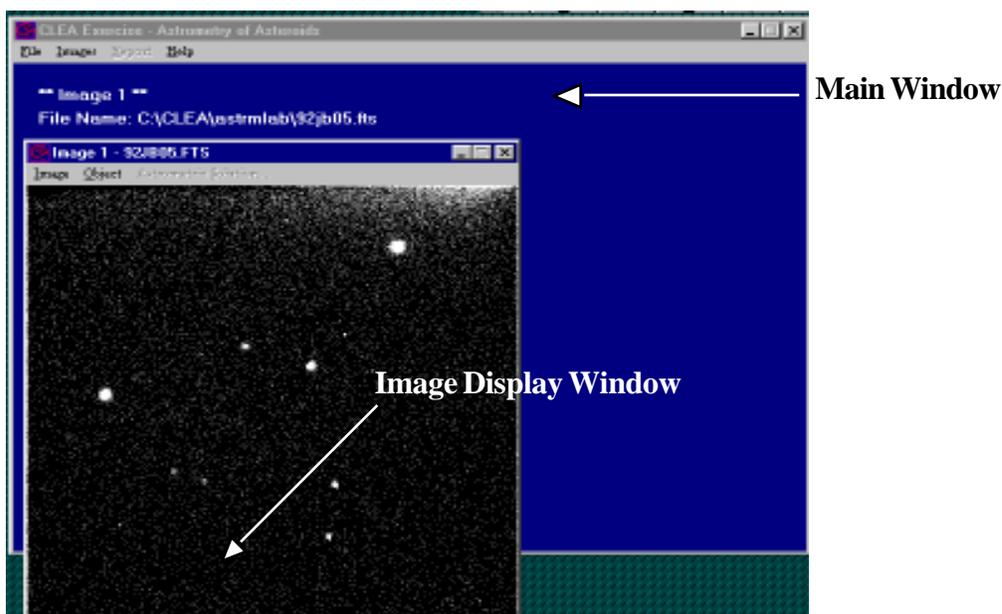


Figure 6
Image Display Window

- The image is oriented with west to the right and north to the top. All of the dots you see on the image are distant stars except one, which is the asteroid. We'll make a chart of the image and mark the asteroid when we discover it. In the blank space located on the following page, make a freehand sketch of the image 92JB05. Try to pay attention to the details—draw it to scale and try to make it fit in the space.

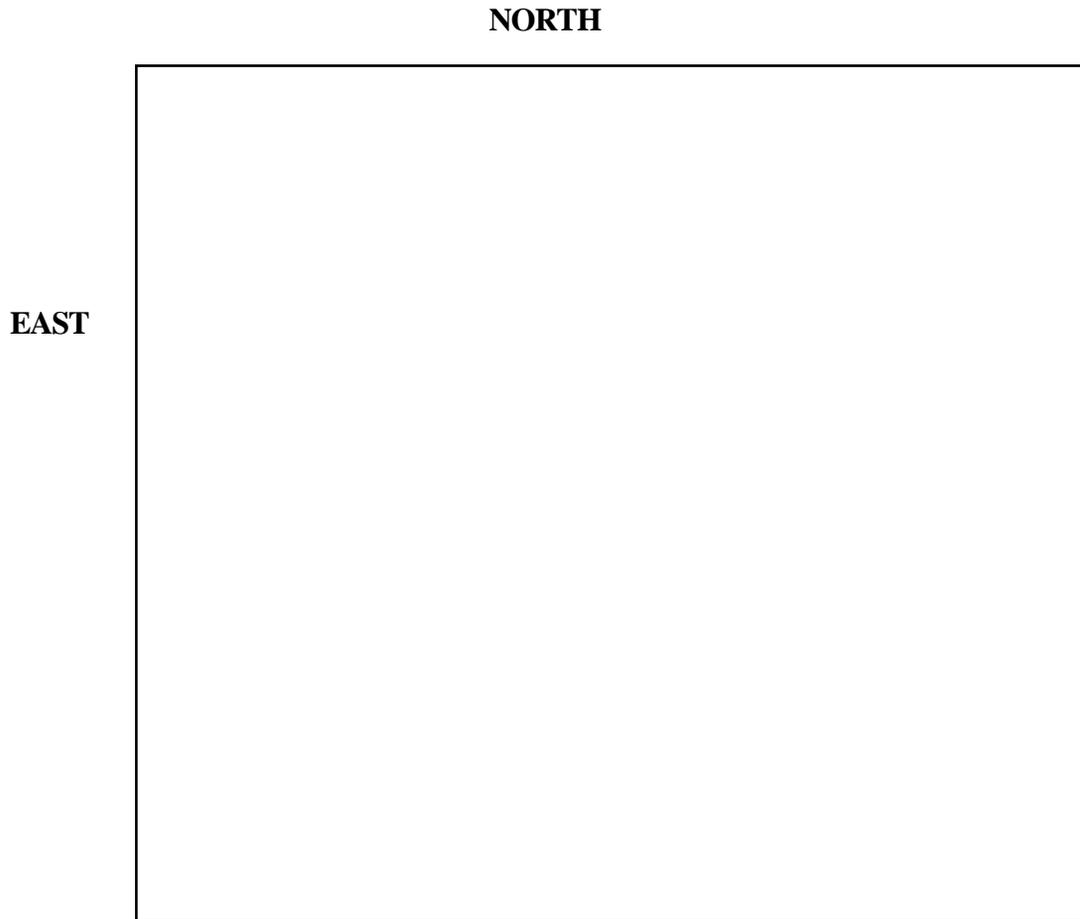


Figure 7
Your Freehand Sketch of the Image

2. Now let's find the asteroid. Load as before, but this time choose **File...Load...Image 2** from the main program window (which appears blue not black as in the **Image 1** window). From the list of images, select **92jb07.fts**, and click **Open** to load it.

You can display this image in its own window by using the **Images...Display...Image 2** selection on the menu bar. Since 92JB07 was taken 10 minutes after 92JB05, the asteroid will have moved. But it may not be immediately obvious which starlike object is out of place, even when you compare the images side by side.

So we blink the images, aligning them so they coincide, and use the computer to flip from one image to the other. Here are the steps we use to blink the images.

- We must first align the images. From the main menu bar located on the blue window, choose **Images...Blink**. You will see one window now, displaying just Image 1.

- At the bottom right, a small instruction box asks you to click on an **alignment** star, which the computer can use to align the two images. If possible, you should try to choose two stars that are on opposite sides of the picture to achieve best results. (*The best combination is a pair of diagonally opposite stars.*) Choose one of the brightest ones, click on it, and note it for your own reference by writing the **number 1** next to it on your freehand drawn chart.
 - Click on **Continue** in the instruction box, and it will ask you for a second alignment star. (*Two stars are needed to account for possible rotation of the images.*) Click on this star, record it on the chart above as **2**, and click again on **Continue**.
 - Now you will see Image 2, and you will be asked to identify star number 1 on Image 2. Check your chart, then click on the same star 1 that you chose in Image 1. If you are satisfied, click **Continue** in the instruction box. You are now asked to identify star 2 and again you click on the same star 2 that you chose in Image 1. Actually, based on your choice of stars in Image 1, the computer will make a good guess as to where the star should be on Image 2. It will draw a box around where it thinks it should be, and if, in fact, it comes close, you need merely click **Continue** to accept its choice. You'll find that the computer does this guesswork in many parts of the program, making it easier for you to make measurements quickly.
 - The computer now has all the information it needs to align the images and blink them. All you need to do is click on **Blink** from the menu bar at the top of the blinking window, and you will see the computer flip back and forth between Image 1 and Image 2 about once a second. The stars will not move, but you should easily be able to pick out the asteroid as the one object that does jump. Be careful when choosing! For example, occasionally a white spot will appear on one image, and not the other. It is not an asteroid, however, but a defect in the picture itself. This is usually caused by radiation—a cosmic ray most often—that exposes a single pixel in the camera during one exposure. You may also notice all the stars brighten and dim, since one image is a longer exposure and therefore brighter. But the asteroid should appear clearly as a smudge of light that changes position from one image to the other.
 - To stop the blinking select **Stop** from the menu bar. To adjust the rate of blinking slower or faster at your convenience, select **Adjust...Blink Rate**. The Blink Rate Interval dialog box appears. The blink rate can be adjusted using the slide bar to increase or decrease the rate per msec that the images blink. The range is from 10 to 1000 msec with the default set at 500 msec.
 - The brightness and contrast of either image can also be adjusted. Select **Adjust...Image Display...Image 1** (or Image 2) from the menu bar. The Adjust Image 1 (or 2) Display Parameter Dialog box appears. Separate slide bar controls are available for the brightness and contrast features. Use the **Initialize...Field Alignment** menu option to choose the alignment stars again.
 - When you have identified the asteroid on Image 1 (92JB05) and Image 2 (92JB07) mark the position of the asteroid with a dot on your chart. On the freehand drawing in Figure 2, neatly label the asteroid's position on Image 92JB05 with a small **05** and its position on Image 92JB07 with an **07**.
3. Now continue to find the asteroid on images 92JB08, 92JB09, 92JB10, 92JB12, and 92JB14 by blinking them using Image 92JB05 as Image 1.

To do this, simply select the **Load...Image2** menu item, and then **Image...Blink** to blink the images. The computer program has a learning feature that will speed up successive measurements. Since you have already blinked one set of images, the next time you blink images, the program assumes that the alignment stars are in the same position. So when you choose **Image...Blink**, you will be shown the blink window. You can realign the images using the **Initialize...Field Alignment** menu choice in the blink window menu box. You'll be prompted for alignment stars, but the computer will show you its guesses first. If the computer's choices are close to the stars chosen for alignment, you need simply to click **Continue** to accept the computer's choices. You can also make your own selection by clicking on the star you want to choose and then click **Continue**.

Repeat this procedure until you've identified a pair of stars on both images.

The procedure will then be the same as you followed with image 92JB07 as Image 2. Again, mark the successive positions of asteroid 1992JB by dots labeled **08**, **09**, **10**, **12**, and **14** on the chart you made in step 1.

- You should note the asteroid is moving in a straight line. Draw an arrow in the space below to show the direction of motion. What direction is this? (North, Northeast, Southeast, etc.)?

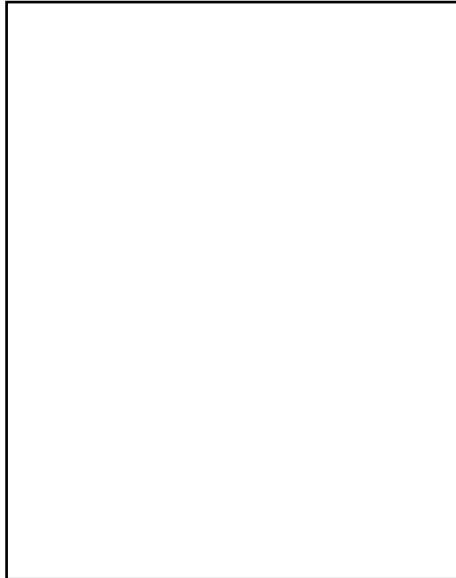


Figure 8
Direction of Motion of the Asteroid

Part II

Measuring the Equatorial Coordinates of an Asteroid by Comparing It to Positions of Known Stars in the *Hubble Guide Star Catalog*

Now that you have identified which object on the image is the asteroid, the next step is to determine the location of the object in the sky by measuring its equatorial coordinates, i.e. the object's Right Ascension and Declination. The computer can do this by a type of interpolation or "fitting" process, which compares the position of the asteroid on an image with the positions of stars whose coordinates have been previously tabulated in a catalog. The most widely used catalog today is an electronic file called the *Hubble Guide Star Catalog (GSC)*, which was originally created to aid in pointing the Hubble Space Telescope. The GSC, as it is called, was created by measuring star positions on photographs of the sky. It contains coordinates and magnitudes of about 20 million stars brighter than apparent magnitude 16. The GSC is available on two CD-ROMS, but to make it unnecessary for you to insert a CDROM into your computer, we have selected part of the GSC and stored it on your computer's hard drive, where the Astrometry program can access it easily.

For each image of 1992JB, you will determine the coordinates of the asteroid by

- Telling the GSC the approximate coordinates of the center of the image, so that it can draw a map of the stars with known coordinates in the vicinity.
- Identify at least three GSC stars that are also on the image, as reference stars for calculating coordinates on the image.
- Point and click on each star on your image that is a reference star, so that the computer knows which star on your image corresponds to a particular reference star in the catalog.
- Point and click on a target object with *unknown* coordinates: the asteroid. The computer then calculates its coordinates with reference to the GSC reference stars you have chosen.
- Store the results of the computer calculation for later printout.
- Write the coordinates of the asteroid in the table at the end of this section.

Procedure for Part II

1. Let's measure the position of the asteroid in Image 92JB05. If it is not already loaded into Image 1, use the **File...Load...Image1** menu choice from the main window to load the file. Then choose the **Images...Measure...Image1** menu choice. A window will open asking you for the approximate coordinates of the center of the image, so that the computer can retrieve data from the proper files in the Guide Star Catalog. You can find the coordinates of the center of these images in the table **Search Images for 1992JB** in Part 2, page 18 of this write-up. Type them into the proper boxes for Right Ascension and Declination. Set the Field size at 8 arcminutes. The images are about 4 arcminutes on a side, but this leaves you some margin for error in finding your reference stars if the field center you specified was a little off. The default value for the magnitude limit is 20. When you have entered the field center information, click OK.
2. The computer will now search for stars in this region in the GSC, and will draw a star chart, based on the GSC coordinates in a window on the left-hand side of the screen. It will display the Image 1, 92JB05, in a window on the right-hand side of the screen. (See Figure 9 on the following page). The Image will show more stars than the GSC map, partly because one of the "stars" is the asteroid, and also because the GSC only includes stars brighter than 16th magnitude, and some of the stars in your images are fainter than that. However, you should see a distinctive pattern of at least three stars in the GSC chart that you can match to the brighter stars on your image.

- When you see the match, you will want to identify it. First sketch the reference stars you are going to pick in the space below, and label them 1, 2, 3, etc.

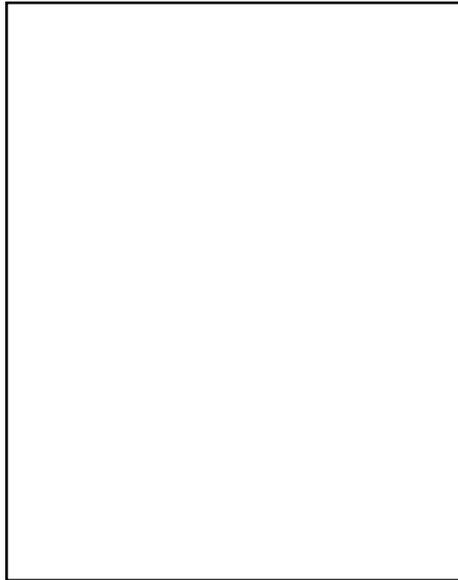


Figure 9
Sketch of Reference Stars

- Now you will tell the computer which ones you've chosen. Using the mouse, click on reference star number one in the left window (the GSC map). A dialog box will open at the bottom of the page, identifying the GSC data on that star; simultaneously the computer will draw a colored box around the reference star on the chart. (Figure 10)



Figure 10
Selecting Reference Stars

Click **select** in the dialog box at the bottom of the page to set your first reference star. Repeat the process for reference star 2, etc. until you have marked as many reference stars as you can see on both the GSC chart and image 92JB05. (You need to identify and mark at least 3, well spaced over as wide an area of the image as possible, for best results.). Record the ID#, RA, and DEC of each reference star in the table below.

<i>Reference Star Coordinates</i>			
Reference Star	ID #	RA	DEC
#1			
#2			
#3			

Figure 11
Table of Reference Star Coordinates

- When you have selected at least 3 reference stars and marked them, go to the **Select Reference Stars** dialog box that is in the bottom center of the screen and click **OK** to tell the computer you're finished selecting stars. If you've only chosen 3, the computer will warn you that more reference stars would give you better results, but if 3 is all you could choose, assure the computer by clicking **NO**, you don't want to choose any more.
- You will now be asked to point to reference star 1, then star 2, etc. in the right window—Image 92JB05. Click on each star in turn, making sure to match it with the reference star you've selected on the GSC chart, and click **OK** on each to signal you've picked the right star. The computer will start to second-guess you—after 2 stars have been identified, it will be able to tell approximately where star 3 is, and if the computer has done a good job (Star 3 is anywhere inside the colored box the computer draws on the screen), you need only click **OK** to accept its choice.

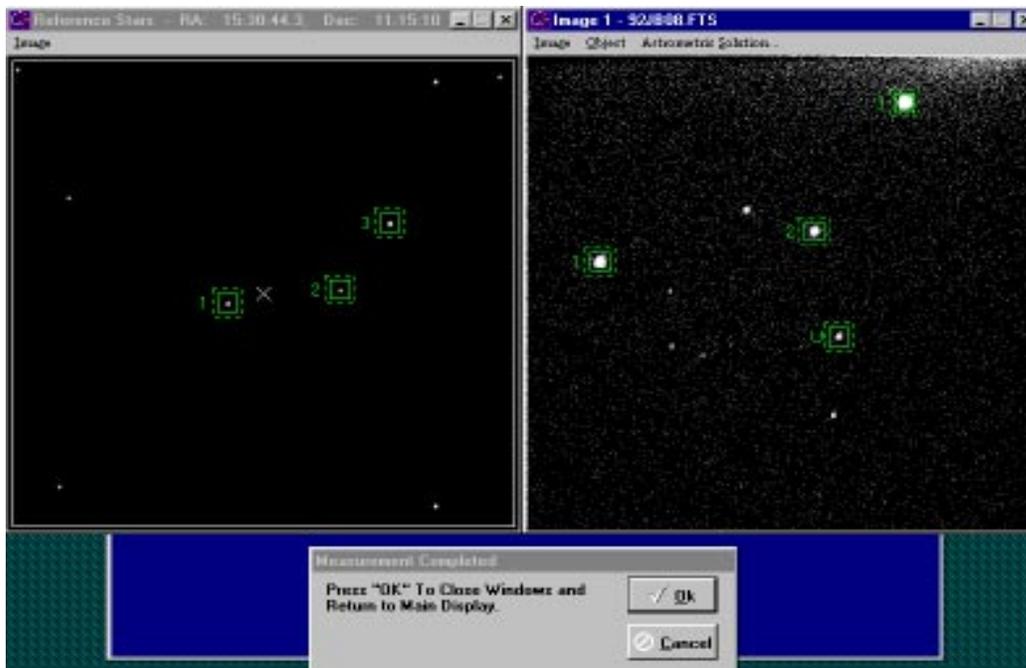


Figure 12
Identification Window

7. When all the reference stars have been identified on your image, the computer will then ask you to point and click on the “unknown” or “target” star—the asteroid. If you click OK after choosing this star, the computer will have enough information to calculate the coordinates of the target star with respect to the reference stars. A small text window will open on the left side of the screen displaying the right ascension and declination coordinates of your target object. Write these down in the proper place in the table at the end of this section. We’ve already written down the measured right ascension of the asteroid 92JB05 to get you started.

8. After you’ve written down the data, click on **OK** in the center box at the bottom to accept the solution.

Then when the computer asks if you want to record the data, click **Yes**, and write the image name (92JB05) in the form labeled **OBJECTNAME**.

Finally click **OK** to record your measurement on a data file. You can view this report form from the Report menu item on the main window at any time for your own reference, and you may want to print it out later when you have added all the other measurements to it.

9. Now use the **File...Load...Image1** menu choice on the main window, along with the **Image...Measure..Image1** menu choice, to measure the asteroid position in images 92JB07, 92JB08, 92JB09, 92JB10, 92JB12, and 92JB14. You will proceed just as you did above, recording your data both on this worksheet and on the computer. You will note that the computer quickly learns the setup you are using—it will know what reference stars you chose the first time, and outline them on the GSC window the next time through. You will still have to match the stars on your image with reference stars on the GSC, and you will, of course, have to show the computer where the asteroid is, since it moves from one image to the next.

The measuring process should be rapid. If you need to change any of the field settings, you can change them in the measuring window using the Image...Adjust...Reference Stars menu, or in the main window by using the File...New...Target Object menu choice, which clears all the images from computer memory and starts over.

10. When you have recorded the positions of the asteroid on all the images, you are ready to proceed to the Part III.

Print out the data using the **Report...Print** menu option. Look at the data you have taken to make sure it makes sense.

The asteroid is moving in a straight line (over the small field of this image—it’s actually going in an orbit around the sun, of course). Therefore you should note a smooth change in the numbers from beginning to end—a regular increase in right ascension (if it’s moving eastward) or decrease (if its moving westward) and a regular increase or decrease in declination (depending on whether it’s moving northward or southward). Re-measure any images that seem to be in error.

Table 1
Information on Images

Search images for 1992 JB				
<i>All images taken on May 23, 1992 at the National Undergraduate Research Observatory, using the Lowell Observatory 0.8 m f/15 telescope. Camera: 512 x 512 Tek Chip with 28 micron pixels</i>				
FILE NAME	RA (2000) of image center (h m s)	DEC (2000) of image center (° ' ")	TIME (UT) of mid-exposure (h m s)	Exposure length(s)
92JB05	15 30 44.30	11 15 10.4	04 53 00	30
92JB07	15 30 44.30	11 15 10.4	05 03 00	120
92JB08	15 30 44.30	11 15 10.4	05 09 00	30
92JB09	15 30 44.30	11 15 10.4	06 37 30	180
92JB10	15 30 44.30	11 15 10.4	06 49 00	30
92JB12	15 30 44.30	11 15 10.4	06 57 00	120
92JB14	15 30 44.30	11 15 10.4	07 16 00	30

Table 2
Measured Equatorial Coordinates

COORDINATES OF ASTEROID 1992JB			
MAY 23,1992			
File Name	Time (UT)	RA(h,m,s)	Dec (° ' ")
92JB05	04 53 00	15 30 38.7	
92JB07	05 03 00		
92JB08	05 09 00		
92JB09	06 37 30		
92JB10	06 49 00		
92JB12	06 57 00		
92JB14	07 16 00		

Part III

The Angular Velocity of Asteroid 1992JB

How fast is 1992JB moving? We can calculate its angular velocity in arcseconds per second of time using data taken in Part II of this exercise (See Table 2). The procedure we follow is to subtract the asteroid's starting position on image 92JB05 from its ending position on image 92JB14, and divide by the number of seconds between the starting image and the ending image. We express this mathematically as

$$\mu = \Delta\theta / \Delta t$$

where μ is the angular velocity of the asteroid, $\Delta\theta$ is the angular distance it moved, and Δt is the time that elapsed.

Procedure for Part III

1. Measuring the elapsed time

- Record the time when image 92JB14 and 92JB05 were taken. (These values are recorded in Table 2, **Measured Equatorial Coordinates**.)

Time of image 92JB14: ____ hours ____ minutes ____ seconds

Time of image 92JB05: ____ hours ____ minutes ____ seconds

- Convert to hours and a decimal to make subtraction easier. (Note: Divide minutes by 60 to get decimal hours, and divide seconds by 3600 to get decimal hours.)
- Add the decimal fractions to the hours to get the final value:

Time of image 92JB14 as a decimal: _____ hours (express to at least 5 decimal places)

Time of image 92JB05 as a decimal: _____ hours (express to at least 5 decimal places)

- Time elapsed between 92JB14 and 92JB05 _____ hours
(Subtract the time when image 92JB05 was taken from the time image 92JB14 was taken.)
- Convert to seconds by multiplying hours by 3600.
- Time elapsed between 92JB14 and 92JB05 _____ seconds.**

2. Measuring the angular distance traveled by 1992JB

In order to calculate the angular distance traveled, $\Delta\theta$, we use the Pythagorean theorem, which states that:

$$c = \sqrt{a^2 + b^2}$$

As illustrated in Figure 6 on the following page, because right ascension and declination are perpendicular coordinates, we can find the total angle moved using this mathematical relationship derived from the Pythagorean theorem.

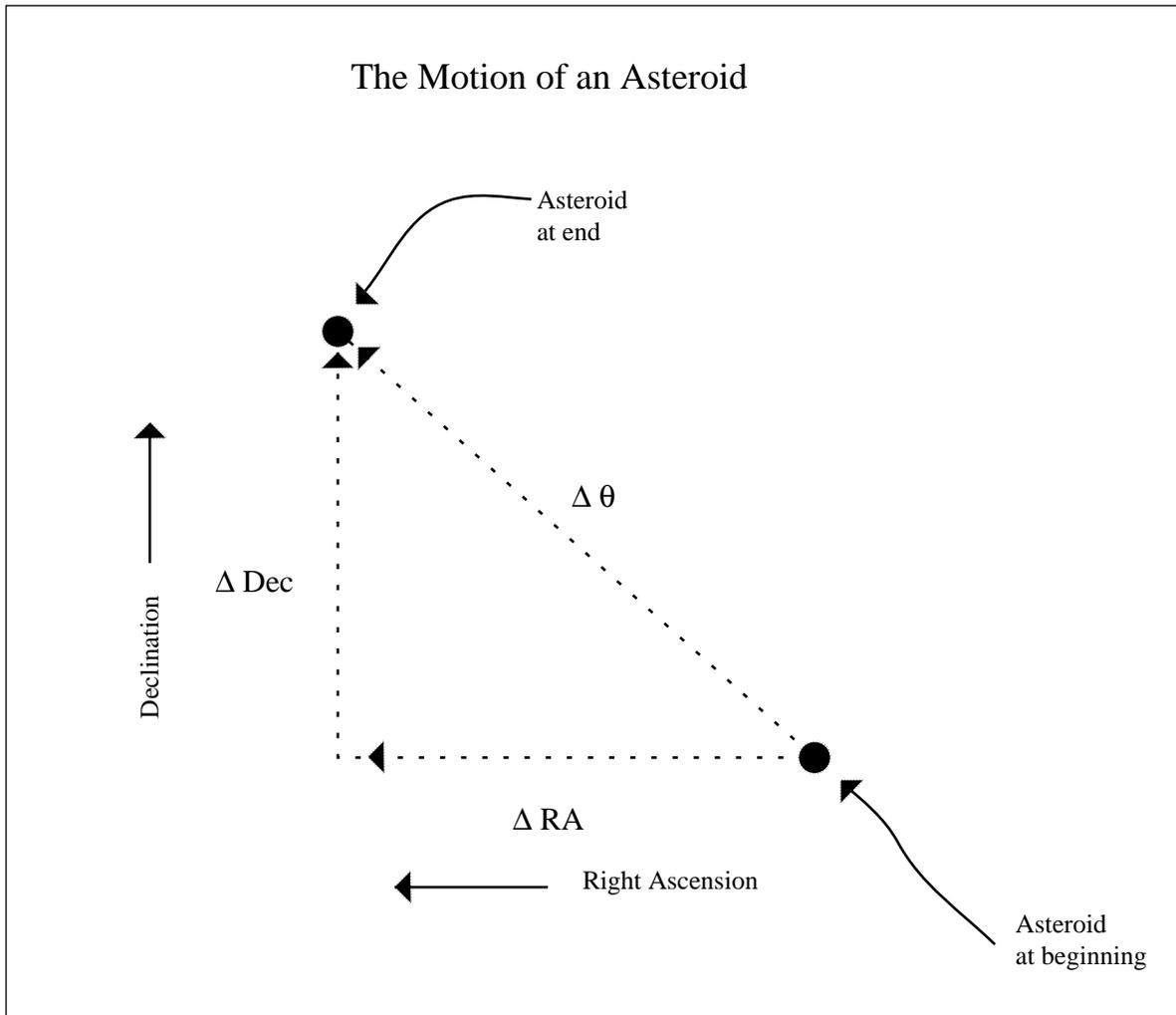


Figure 13
The Mathematical Illustration of the Motion of an Asteroid

Using Figure 6 as a guide , if we let ΔRA represent the change in the number of arcseconds in right ascension, and ΔDec represent the change in the number of seconds moved in declination, then using the relationship expressed by the Pythagorean theorem, we can construct the following equation to determine the total angle moved.

$$\Delta\theta = \sqrt{(\Delta RA)^2 + (\Delta Dec)^2}$$

- Record the values for the declination of images 92JB14 and 92JB05 below. (These values are recorded in Table 2, *Measured Equatorial Coordinates.*)

Declination of asteroid on 92JB14 ____ ° ____ ' ____ "

Declination of asteroid on 92JB05 ____ ° ____ ' ____ "

- Convert to decimal degrees just as you converted to decimal hours above. (That is divide ' by 60 and " by 3600 to get the decimal values.)

- Add the decimal values to get the value final:

Declination of asteroid on 92JB14 _____° (express to 5 decimal places)

Declination of asteroid on 92JB05 _____° (express to 5 decimal places)

- Subtract to find the change in declination

ΔDec _____° (express to 5 decimal places)

- And finally convert to arcseconds " by multiplying by 3600.

ΔDec _____"

- Repeat the previous steps to calculate **ΔRA**

- Record right ascension values for each image below from Table 2, **Measured Equatorial Coordinates**

Right Ascension of asteroid on 92JB14 ____ h ____ min ____ sec

Right Ascension of asteroid on 92JB05 ____ h ____ min ____ sec

- Convert to decimal hours:

Right Ascension of asteroid on 92JB14 _____ h (5 decimal places)

Right Ascension of asteroid on 92JB05 _____ h (5 decimal places)

- Subtract to find the change in right ascension:

ΔRA _____ h (5 decimal places)

- Convert to seconds of RA by multiplying by 3600:

ΔRA _____ h (5 decimal places)

- BUT WAIT! We're not done yet—1 second of RA is 15 arcseconds times the cosine of the declination. (Remember the RA lines come together at the poles, and so there are smaller angles between them at high declination. Multiplying by the cosine of the declination adjusts for this physical change). For declination you can use the value of the declination you recorded for either image (in decimal degrees) in the previous steps:

$$\Delta RA \times 15 \times \cos(\text{Dec}) =$$

$$\Delta RA = \text{_____} "$$

- Using the **Angular Distance Traveled Formula**,

$$\Delta \theta = \sqrt{(\Delta RA)^2 + (\Delta Dec)^2}$$

$$\Delta \theta = \text{_____} "$$

4. Calculating the angular velocity of Asteroid 1992JB on May 23, 1992:

$$\mu = \frac{\Delta\theta}{\Delta t}$$

$\Delta\theta =$ _____ "/second.

Note: We've only calculated the angular velocity of the asteroid. We need to know its distance to calculate how fast it's traveling in km/second. We will calculate the distance of 1992JB in the next section, using the method of parallax.

Part IV

Measuring the Distance of Asteroid 1992JB by Parallax:

In this section we'll use our new-found skill in measuring coordinates to determine the parallax of asteroid 1992JB. For this purpose, we took two images of 1992JB *simultaneously* from observatories at opposite sides of the United States. One image, you have already seen: Image 92JB12, which we have also stored under the name ASTWEST. It was taken by Dr. Laurence Marschall using a 0.8m diameter telescope at the National Undergraduate Research Observatory in Flagstaff, Arizona. The other image ASTEAST was taken by Dr. Thomas Balonek using an 0.4 m telescope at the Foggy Bottom Observatory of Colgate University in Hamilton, New York.

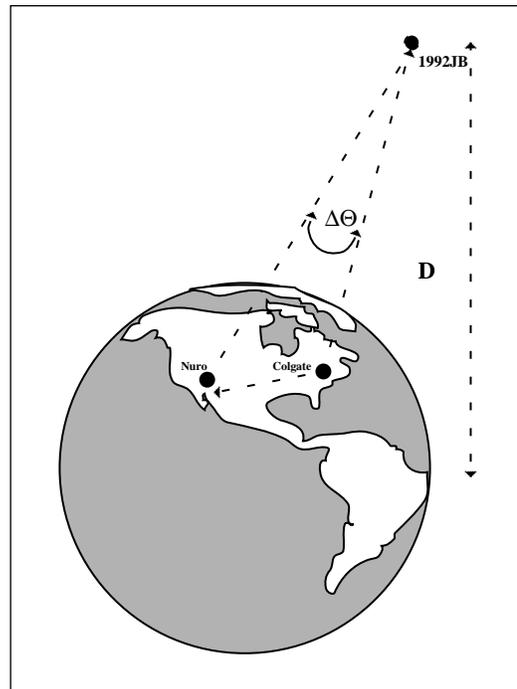


Figure 14
Parallax Observations
1992JB

Time of Observation at Both Sites				
06 57 00UT 23 May, 1992				
Site	Latitude	Longitude	Image File	Exposure
Foggy Bottom Observatory, Colgate University Hamilton, NY	42° 48' 59.1"	W 75° 31'59.2"	ASTEAST	120
National Undergraduate Research Observatory Flagstaff, AZ (Telescope Operated by Lowell Observatory)	35° 05' 48.6"	W 111° 32' 09.3"	ASTWEST	120

Because the asteroid is much closer than the stars, it appears in a different position on the two images with respect to the background stars. This is called its *parallax*. By measuring the position with respect to reference stars on both pictures, we can determine the parallax, which is just the angular difference, $\Delta\theta$, in arc seconds, between its position on the image taken from the eastern site and from the western site. Using simple trigonometry (see Figure 7 as the example), if B , the *baseline*, is the distance between the two telescope sites in kilometers, then :

$$\text{Dist. of the Asteroid} = 206,265 \left(\frac{B}{\Delta\theta} \right)$$

Using our program, then, the measurements can be done rather quickly.

Procedure for Part IV

1. Loading the Images

Load **ASTEAST** as **Image 1**. Load **ASTWEST** as **Image 2**. Display the two images side by side for comparison. Note that the two cameras had different sensitivities (the east-coast telescope was smaller), and had CCD chips of different dimensions, so the images don't look quite the same. But the same reference stars are visible on both images. Find asteroid 1992JB again on each image (you can refer to your chart in part 1—remember ASTWEST is 92JB12)

- Look at image ASTWEST. Compared to its position on ASTEAST, does 1992 JB look further to the east or further to the west with respect to the background stars? _____.
- Why is this what you'd expect? — explain using a diagram in the space below.

2. Measuring the coordinates of the asteroid in ASTEAST and ASTWEST

Now using the methods you learned in part 2, measure the coordinates of the asteroid in ASTEAST and ASTWEST. You can use the **Images...Measure...Image 1**, and **Images...Measure...Image2** menu options on the main window. Tabulate your results below.

Measurement of Coordinates for ASTEAST and ASTWEST

File	RA (h m s) of 1992JB	Dec (° ' ") of 1992JB
ASTEAST	_____	_____
ASTWEST	_____	_____

3. Calculating the parallax of 1992JB

The parallax of 1992JB is just the difference between the two positions. We can follow the methods of calculating the angular difference between two positions that we used Part 3. We separately calculate the difference in the declinations and the difference in the right ascensions in arcseconds (") and then find the total angular difference as the square root of the sum of the squares of the declination and right ascension differences.

- Express the coordinates of 1992JB on both images in decimal form to make subtraction easier:

File	RA (h.xxxxx) of 1992JB	Dec (°.xxxxx) of 1992JB
ASTEAST	_____	_____
ASTWEST	_____	_____

- Express the difference ΔDec in decimal degrees: _____ °

Convert to arcseconds by multiplying by 3600.

$$\Delta\text{Dec} = \text{_____}''$$

- Express the difference ΔRA in decimal hours: _____ h

Convert to seconds by multiplying by 3600 ΔRA : _____ sec

Convert to arcseconds by using the equation

$$\Delta\text{RA} \times 15 \times \cos(\text{Dec}) = \text{_____}$$

$$\Delta\text{RA} = \text{_____}''$$

- Calculate the total parallax in arcseconds:

$$\text{Parallax} = \sqrt{(\Delta\text{RA})^2 + (\Delta\text{Dec})^2}$$

$$\text{Parallax} = \text{_____}''$$

4. Calculating the distance of Asteroid 1992JB:

Knowing the parallax of Asteroid 1992JB when seen from the Flagstaff, AZ as compared to Hamilton, NY, and knowing *baseline*, i.e. the separation of the two telescopes (3172 kilometers). We can use a simple trigonometric formula to calculate the distance of the asteroid.

$$\text{Dist. of Asteroid} = 206,265 \left(\frac{\text{Baseline}}{\text{Parallax}} \right)$$

Where the baseline and the distance are both expressed in kilometers and the parallax in arcseconds.

- Using this formula, calculate the distance of 1992JB on May 23, 1992 at 06 57 UT.

Distance of 1992JB = _____ km.

Distance of 1992JB = _____ Astronomical Units.

- Compare this with the distance of the moon. How many times further or closer is it than the moon? _____.

- Asteroids are classified by their average distance from the sun. *Belt Asteroids* orbit in the asteroid belt; *Trojan Asteroids* orbit at the same distance as Jupiter. *Near-Earth* or *Earth Approaching* asteroids have orbits that bring them near the earth. What kind of an asteroid do you think this is? Why?

Part V: The Tangential Velocity of Asteroid 1992 JB:

The tangential velocity, V_t , of an asteroid is the component of its velocity perpendicular to our line of sight. Again, a simple trigonometric formula lets you calculate its velocity in kilometers/second if you know its angular velocity (μ , in "/sec) and its distance (km). We determined the angular velocity in Part 3 and the distance in Part 4 of this exercise. Then it follows that the tangential velocity is represented as:

$$V_t = \frac{(\text{angular velocity} \times \text{dist.})}{206,265}$$

- So using our results, calculate the tangential velocity of the asteroid.

$V_t =$ _____ **km/sec**

Optional Questions and Activities

QUESTION 1

Is the value you get for the tangential velocity a reasonable one?

Why not calculate the orbital velocity of the earth for comparison? To do so, look up the orbital radius of the earth, and divide the circumference of the earth's orbit with its orbital period in seconds (1 year = 3.1×10^7 seconds) to determine the earth's orbital velocity.

Would you expect an asteroid to have a lower or higher orbital velocity than the earth? Why?

How does this asteroid's velocity compare to the orbital velocity of the earth?

What factor has been neglected in interpreting the tangential velocity we have measured as the orbital velocity of the asteroid?

Optional Activity

Use the Astrometry program to analyze a set of image pairs provided by your instructor. (These images pairs are listed in the table below.) For each image pair, blink the images, and try to find an asteroid. Note your findings in the table. If there is an asteroid, measure its coordinates.

Note: Coordinates of standard stars are provided for *only one* asteroid in the program, therefore you will only be able to determine the coordinates of one asteroid.

Identifying An Asteroid		
Image Pair	Asteroid Identified (yes or no)	Coordinates of the Asteroid
A1/A2		
B1/B2		
C1/C2		
D1/D2		
E1/E2		
F1/F2		
G1/G2		
H1/H2		
I1/I2		
J1/J2		

References

Laurence A. Marschall, "Coordinates and Reference Systems", in *The Astronomy and Astrophysics Encyclopedia*, Stephen P. Maran, ed., New York Van Nostrand Reinhold, 1992, pp. 131-133.