Astrometry of Asteroids

Student Manual and Worksheet
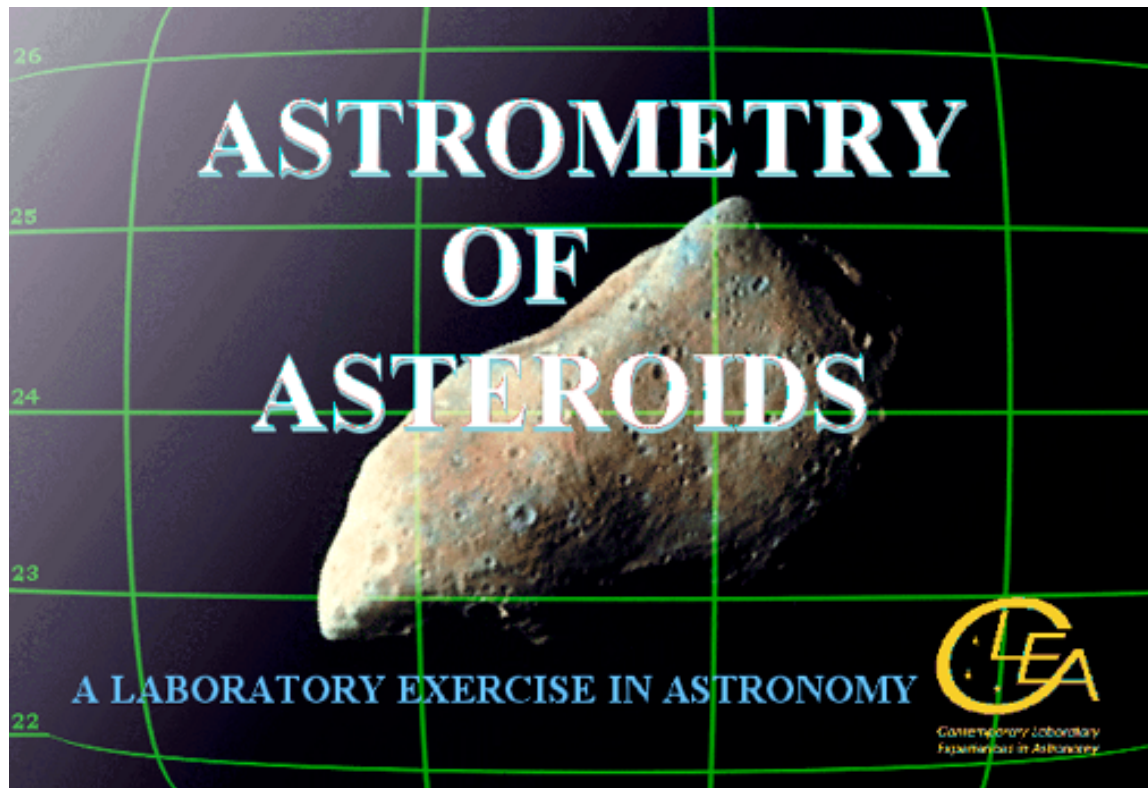
Goals

Overall

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

You should understand the fundamentals of using the equatorial coordinate system of right ascension and declination 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.

Specific

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					
Angular Velocity	*AU*	*Degrees*	*Parallax*	*Universal Time*	*Minutes*
arcminutes	*Blinking*	*Hours*	*Proper Motion*	*arcseconds*	*Seconds*
Asteroids	*Coordinates*	*Magnitude*	*Right Ascension*	*Declination*	

The Computer Program

The program we will use (ASTROMETRY OF ASTEROIDS) can be downloaded to your computer, or you can go to any of the computer labs (running Windows) and look in the Programs for ASTRO 121 menu (for ICS labs) for the Asteroid Program or the ASTRO 150 menu (for ATLAS labs). Or, if you want to install on your own machine, download from http://www3.gettysburg.edu/~marschal/clea/astlab.html and install the AstrmLab.EXE program.

Introduction

Astrometrical Coordinate systems and the Technique of Astrometry

This lab involves 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 some stars. Parallax is a semi-annual wobble 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 continuous 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 an extremely 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 orbital 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
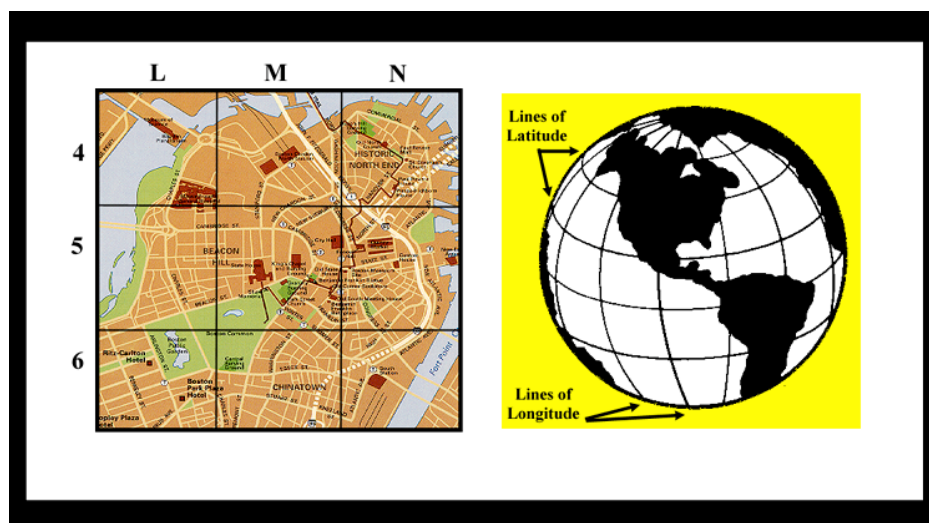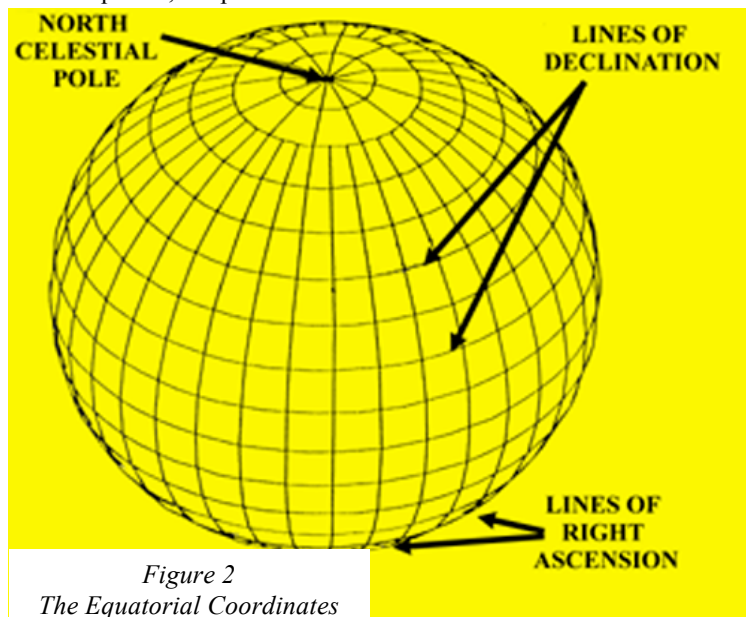

Figure 1
Coordinate Systems

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, which 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 40 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.

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 graph. 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 this system is 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 (°), 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° 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 (H), minutes (m) and seconds (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. 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

Figure 2
The Equatorial Coordinates

catalogs is called the *FK5 Catalo*g, 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* contains only 3522 stars, all of them rather bright. The right ascension and declination 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 G*SC*, 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 *FK5Catalog*, 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 the 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, as a planet or asteroid does), 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 from that of other nearby stars 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).
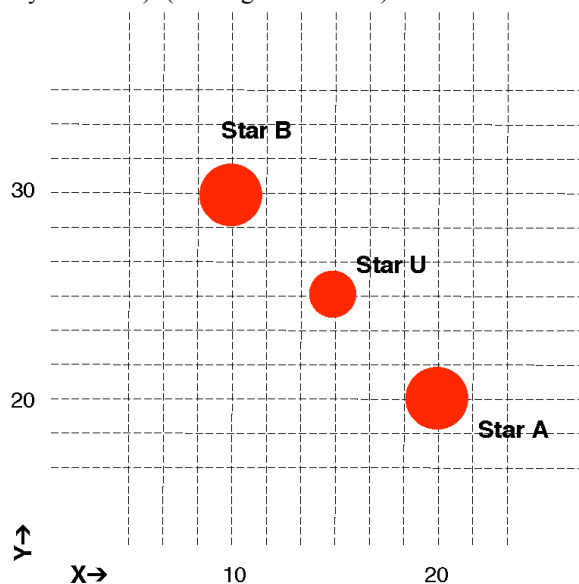

Figure 3
Determining the Coordinates
of an Unknown Object

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 halfway 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 arc. That's approximately the angular diameter of a dime seem 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	5h 0m 0s	10° 0' 0"	20	20
Star B	6h 0m 0s	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 only 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). 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 to 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.
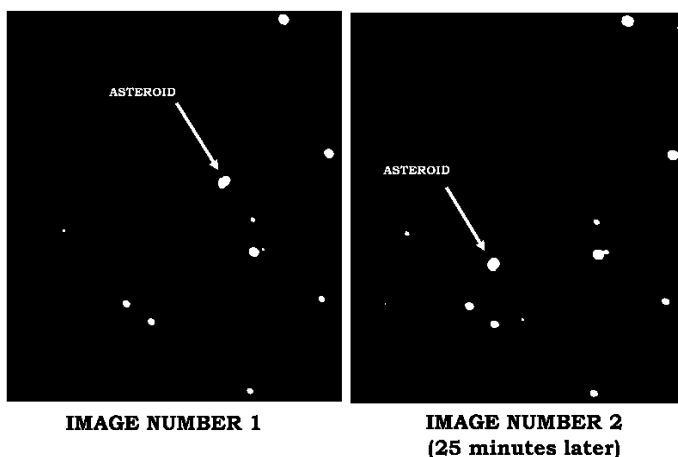

IMAGE NUMBER 1

IMAGE NUMBER 2
(25 minutes later)

Figure 4
Finding the Asteroid

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. Seeing the asteroid continue its trend of motion in a third image can confirm your identification.

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 makes possible 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.

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 Θ**/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.
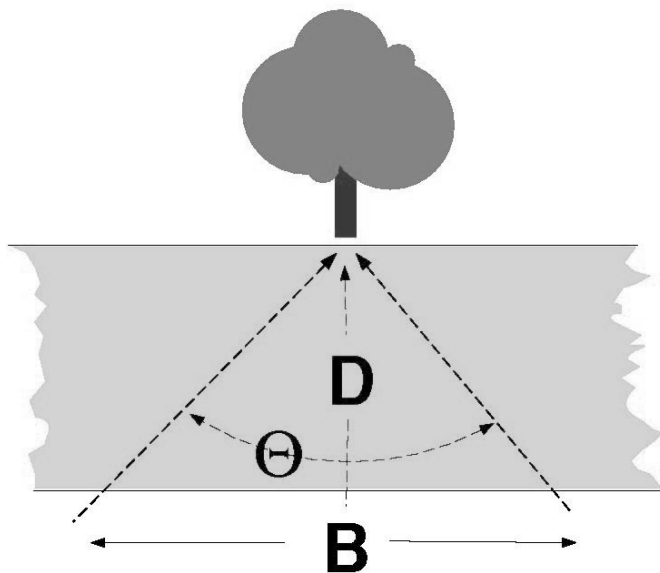

Figure 5
Parallax of an Object

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.

Overall Software 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, 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

Under a typical installation, you will find *Astrometry of Asteroids* under **CLEA Exercises** in the **Programs** section of the Windows **Start** menu. If this is not the case, consult the lab help desk. When the program starts, the CLEA logo should appear in a window on your screen. Select **Login >** under the **File** menu. Fill in the form that appears. When you have completed the form and clicked **OK**, the opening screen of the *Astrometry of Asteroids* lab will appear.

Accessing the HELP Files
You may, at any time, select **Help** from the menu. Within **Help…Topics**, there are five options that you can select: **Login, Files, Images, Reports,** and **Close the Progra**m. **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 for any unsaved data. There is no user help for this program; therefore the **User** option is disabled. **About This Exercise** displays the title and version number of the program as well as the copyright information.

Part I Finding Asteroids by Blinking Images

This software includes 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 (aster-oid = "starlike"), looks just like a star.

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 *blinkin*g. 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. **Below, the formal lab discussion is followed. At the end of this document, is the portion that should be turned in for credit, the Worksheet. DO NOT turn in this entire document. Write all answers to the embedded questions into the appropriate places of the worksheet.**

Procedure for Part I

1. Let's look at one of the images. From the menu bar, choose **File… Load Image Files… 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 image has been loaded, but is not yet displayed. To display it, select **Images** on the menu bar, then choose **View/Adjust… Image 1** from the pull-down menu. A window showing the image 92JB05 will appear on your screen.
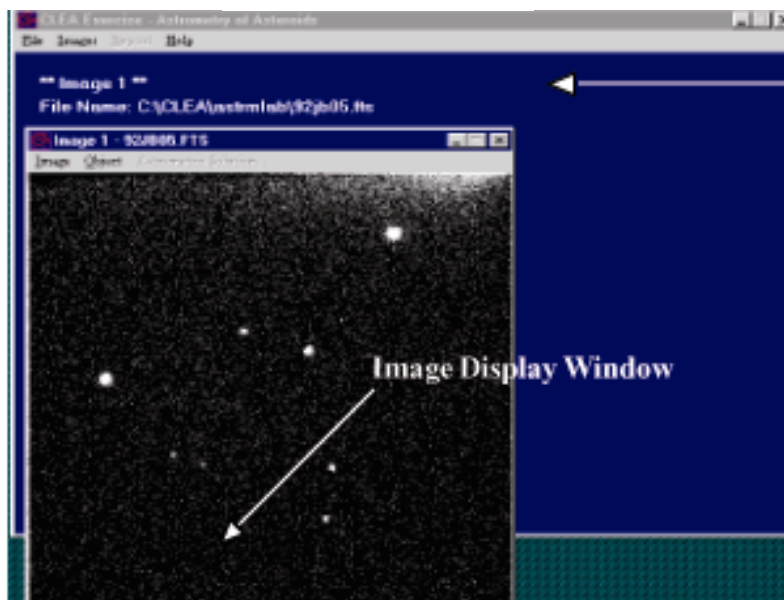
Main Window

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 *worksheet* at the end of this document, Figure W1, 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.

2. Now let's find the asteroid. Load as before, but this time choose **File…Load Image Files …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.
- **NOTE: The program can load up to four image files for blinking purposes, but for first-time users we recommend blinking only two at a time. Thus you will be loading images only in the** Image 1 **and** Image 2 **slots. If at some point you wish to blink more than two images, try** File > Load Image Files > Multiple Load**. Then use the CTRL key to select multiple images.**
You can display this image in its own window by using the **Images. ..View/Adjust…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 star-like object is out of place, even when you compare the images side by side.

So we blink the images, first aligning them so they coincide, and then using 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. Similarly, the background shade may be lighter in one image than in another. 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.

- To start over, select the **Adjust…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 (Figure W1 on the Worksheet). On the freehand drawing of Figure W1, 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. You will continue to use Image 92JB05 as Image 1.

To do this, simply select the **Load…Image2** menu item, and then **Image…Blink** to blink the images. You will be prompted to identify the alignment stars on the new image. Continue with images 09-14.

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 (Figure W1).

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 images 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 CD 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.

- Identifying at least three GSC stars that are also on the image, as reference stars for calculating coordinates on the image.

- Pointing and clicking 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.

- Pointing and clicking 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.

- Writing the coordinates of the asteroid in the table on the Worksheet.

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 Image Files…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 to confirm the Observation Date and Time. Click OK. A second window will open asking you to confirm the coordinates for the center of the field with those in Table 1 on page 14. Set the Field Size at 8 arcminutes. The default value for the magnitude limit is 20. When you have entered the field center information, click OK. This second window will only open the first time through this measurement. If you should need to change the information, you will need to cancel the reference parameters by going to **File….Clear Images/Ref Fields…Reference Fields Only.**

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 7). 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. *Note that the scale of the chart will not match the scale of the image.*

3. When you see the match, you will want to identify it. First sketch all the reference stars from the reference star window on the left in Figure W3, then label the three stars you will use 1, 2, and 3 on Figure W3.

4. 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 7).
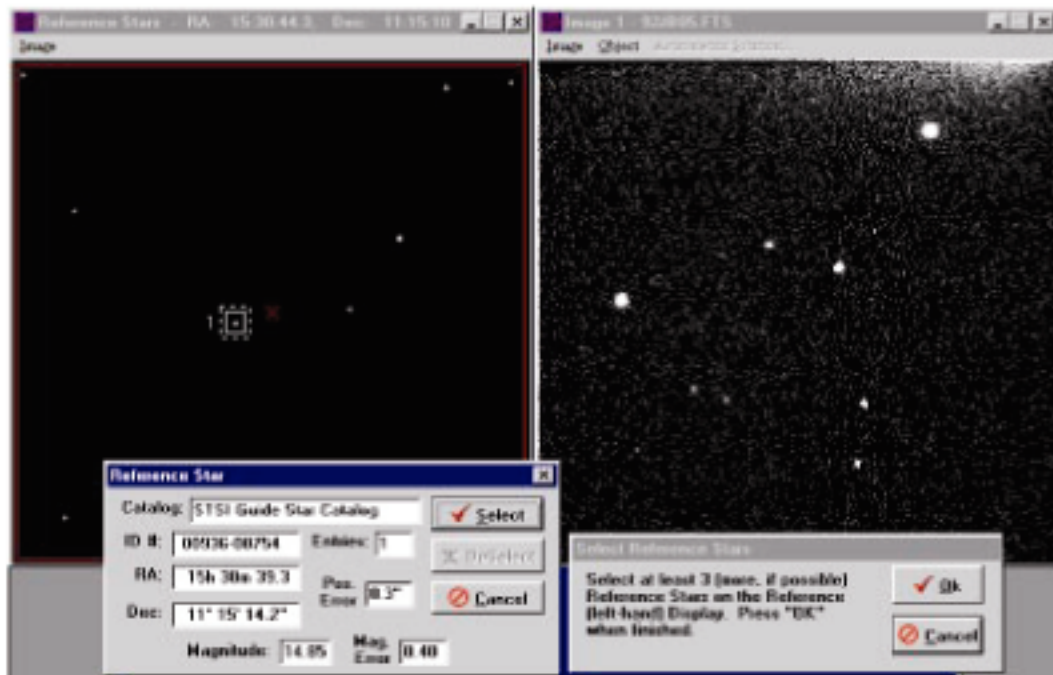

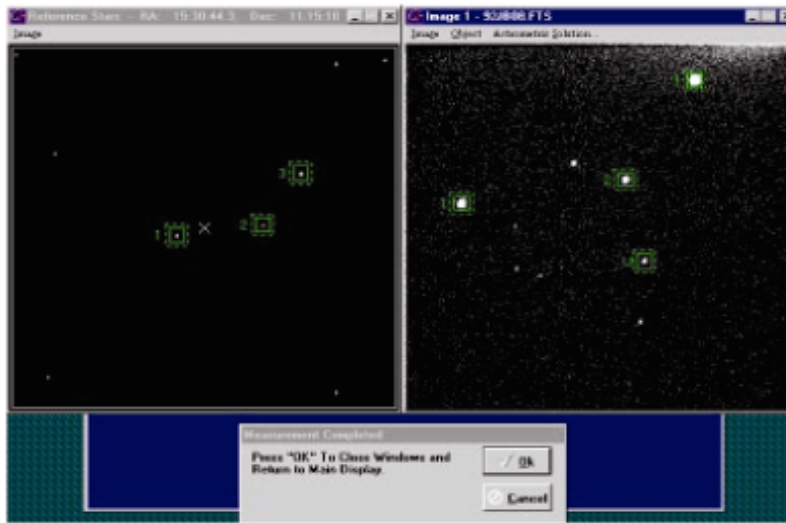*Figure 7*
Selecting Reference Stars

Record the ID#, RA, and DEC of each reference star in Table W1 in the Worksheet.

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.).*

5. 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.

6. 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 8
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 Table W2 in the worksheet. 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.**

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 Image Files…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 the worksheet Table W2 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 by using the **File…Clear Images/Ref. Fields** 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.
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				
All images taken on May 23, 1992 at the National Undergraduate Research Observatory, using the Lowell Observatory 0.8 m f /15 te Camera: 512 x 512 Tek Chip with 28 micron pixels				
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

Note: Some of the above data may differ from the data that appears in the computer window when the file is loaded. You do not need to correct the information stored in the software and you may just click OK.

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. 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

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

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

Follow the calculations step by step in the worksheet.

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.
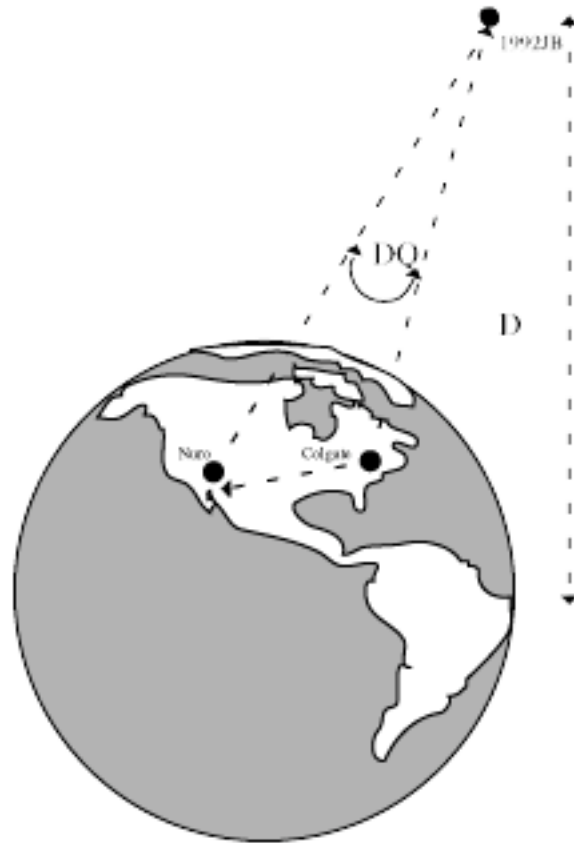

Figure 9
Parallax Observations
1992JB

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 byLowell Observatory)	35° 05' 48.6"	W111° 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 5 as the example), if **B**, the *baseline*, is the distance between the two telescope sites in kilometers, then :

Dist. To the Asteroid = 206,265(B / $\Delta\theta$)

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)

    Use the images to answer the questions on the worksheet.

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 on the worksheet.

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. Show all your work in the worksheet.

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). Use the worksheet to calculate the velocity of asteroid 1992 JB.

WORKSHEET: **Name:**

Part I.

1. Sketch image 92JB05 in the box below.
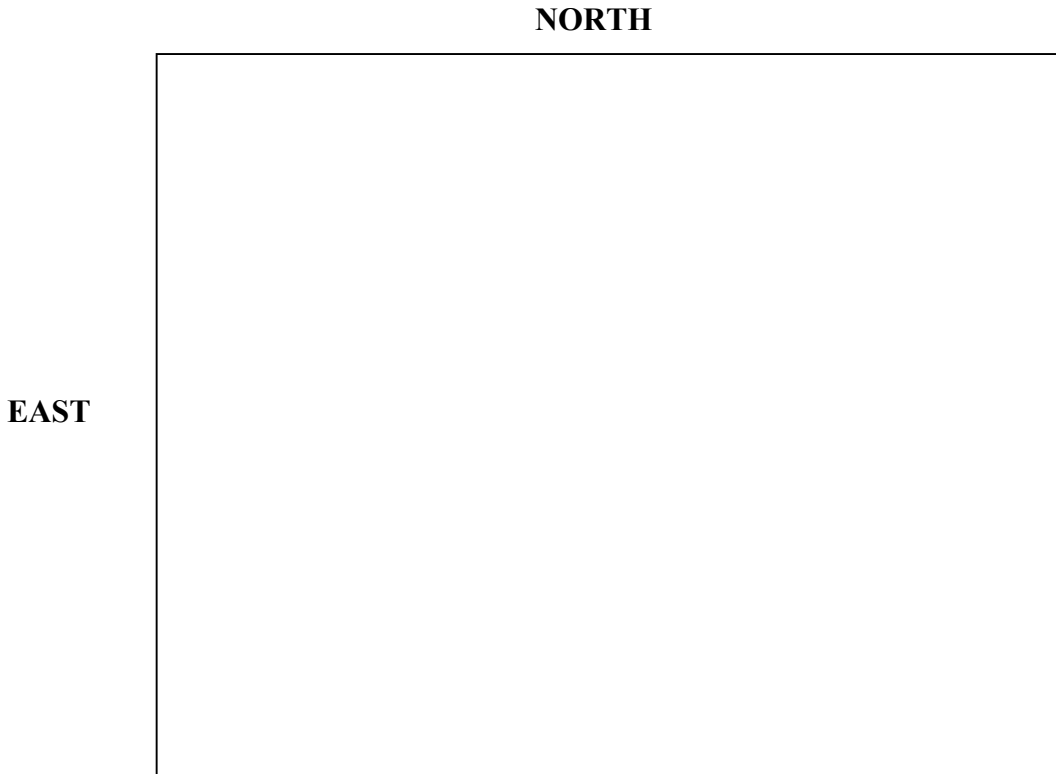
NORTH

EAST

Figure W1
Your Freehand Sketch of the Image

2. Choose one of the brightest stars from the images, click on it, and note it for your own reference by writing the **number 1** next to it on your freehand drawn chart. Then, choose the second star form location reference and write a **number 2** next to it.

3. 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 W1, neatly label the asteroid's position on Image 92JB05 with a small **05** and its position on Image 92JB07 with an **07**.

4. After blinking through 92JB08, 92JB09, 92JB10, 92JB12, and 92JB14, mark the successive positions of asteroid 1992JB by dots labeled **08**, **09**, **10**, **12,** and **14** on Figure W1.

5. Draw an arrow in the space below (Figure W2) to show the direction of motion. Don't forget the orientation of the image is different from what would be found on a traditional land map; see *Figure W1*.

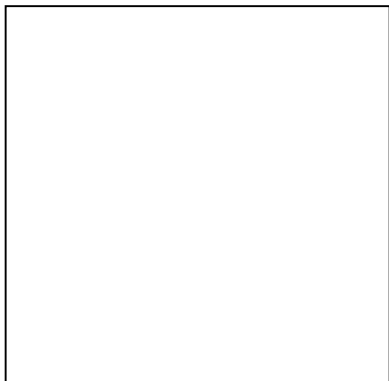6. What direction is this? (North, Northeast, Southeast, etc.)?

Figure W2
Direction of Motion of the Asteroid

Part II.

1. After you match the GSC stars on the field, sketch all the reference stars from the reference star window on the left in the space below, then label the three stars you will use with 1, 2, and 3.
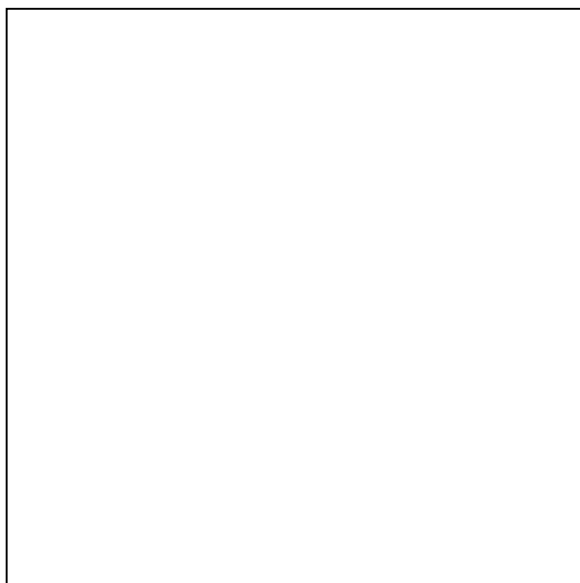

Figure W3
Sketch of Reference Stars

2. Following the instructions, fill in Tables W1 and W2.

Table W1
Table of Reference Star Coordinates

Reference Star	ID #	RA	DEC
# 1			
# 2			
# 3			

Table W2
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		

Note: All the values for RA should be approximately the same.

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 W2). 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

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

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

For your guidance in these calculations, approximate values appear in parenthesis beside some key answers. These are ballpark figures given to help reduce calculator errors. You should record your calculated values even if they are not near the given values.

Procedure for Part III

SHOW ALL YOUR WORK

1. Measuring the elapsed time
    a.   Record the time when image 92JB14 and 92JB05 were taken. *(These values are recorded in Table W2, Measured Equatorial Coordinates, in* **Column 2 Time (UT)***.)*

        Time of image 92JB14: ____hours ____minutes _____seconds

        Time of image 92JB05: ____hours ____minutes _____seconds

    b.   Convert the hours to seconds to make subtraction easier. *(Note: Multiply minutes by 60 and hours by 3600 and add all the values together.)*

        Time of image 92JB14: _____seconds

        Time of image 92JB05: _____seconds

    c.   Subtract the time when image 92JB05 was taken from the time image when image 92JB14 was taken.

        Time elapsed between 92JB14 and 92JB05 Δt = _____seconds   (8500)

2. Measuring the angular distance traveled by 1992JB

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

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

As illustrated in Figure W4, because right ascension and declination are perpendicular coordinates, we can find the total angle moved using this mathematical relationship derived from the Pythagorean theorem.
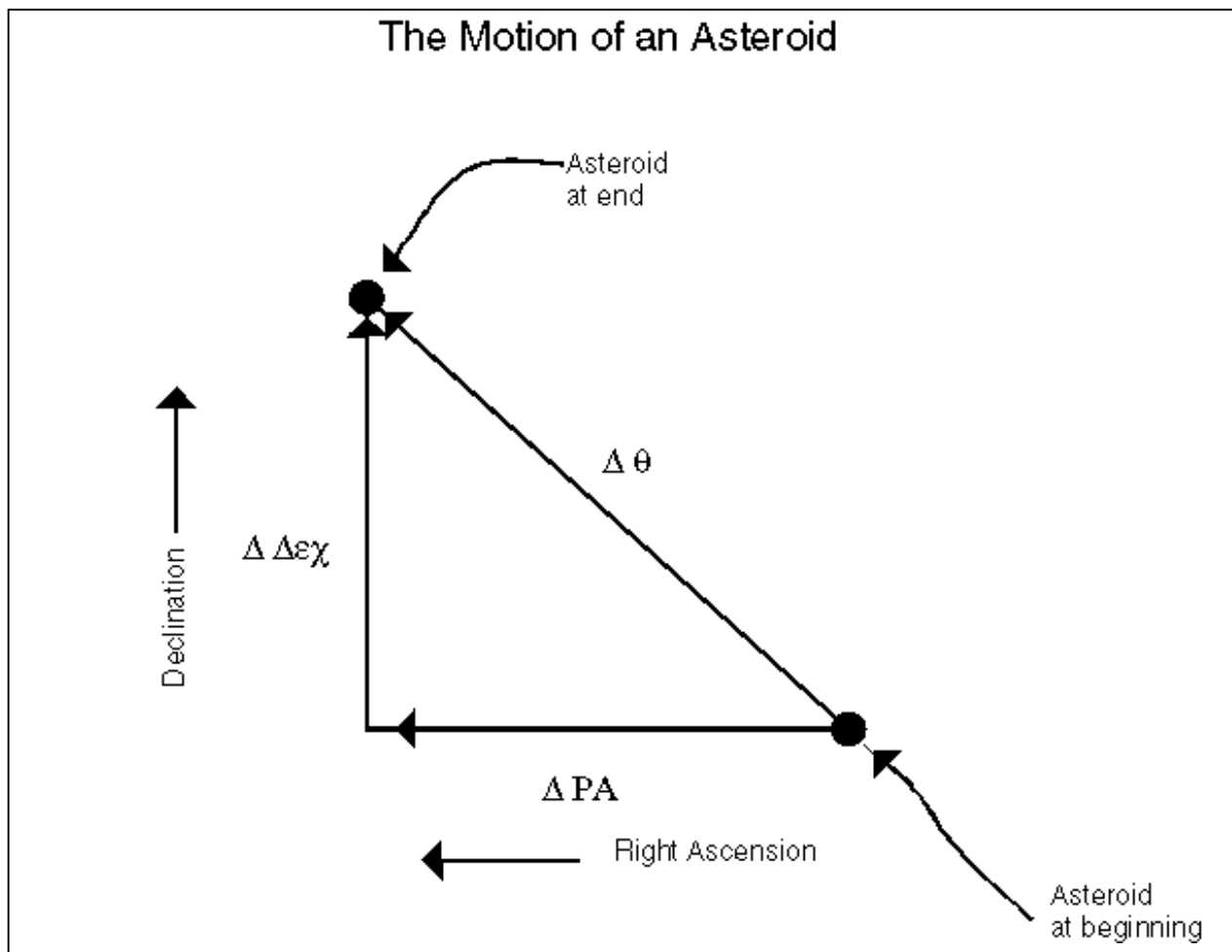
The Motion of an Asteroid

Asteroid
at end

$\Delta\,\theta$

$\Delta\,\Delta\varepsilon\chi$

Declination

Δ PA

Right Ascension

Asteroid
at beginning

Figure W4
The Mathematical Illustration of the Motion of an asteroid

Using Figure W4 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.

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

   d.   Record the values for the declination of images 92JB14 and 92JB05 below. (*These values are recorded in Table W2, Measured Equatorial Coordinates.*)

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

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

e. Convert to arcseconds just as you converted to seconds in 1-b above. *(That is multiply ' by 60 and ° by 3600 and add all the values together.)*

Declination of asteroid on 92JB14 _____"

Declination of asteroid on 92JB05 _____"

f. Subtract to find the change in declination

ΔDec_____" *(100)*

g. We will need **ΔDec** in degrees in step k later, so we will convert the result from f in arcseconds to degrees now, by dividing by 3600.

ΔDec_____° *(0.03)*

h. Record right ascension values for each image below from Table W2, Measured Equatorial Coordinates.

Right Ascension of asteroid on 92JB14 _____ h _____min _____sec

Right Ascension of asteroid on 92JB05 _____ h _____min _____sec

i. Convert to seconds:

Right Ascension of asteroid on 92JB14 _____seconds

Right Ascension of asteroid on 92JB05 _____seconds

j. Subtract to find the change in right ascension:

ΔRA_____ seconds

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). *Use* **Declination** *for the image center, any of the values on Table W2 will do, and you can round them to the nearest degree for simplicity! Note: Make sure your calculator is in Degrees Mode.*

k. **ΔRA(") = ΔRA(sec) x 15 x cosine(Declination(°)) = _____ "**

l. Using the **Angular Distance Traveled Formula**, calculate **Δθ,** using **ΔRA** in arcseconds from step k and **ΔDec** in arcseconds from step f .

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

= _____" *(100)*

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

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

m. Calculate **μ** by using **Δθ** from step l and **Δt** from step c.

μ = _____ "/second. *(0.01)*

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

Part IV

1. Using the images, address the following questions:

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? _____

Using words and/or a diagram, try to explain why the position appears to shift, and explain the definition of parallax.

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***

    SHOW ALL YOUR WORK.

    a. Express the coordinates of 1992JB on both images in seconds to make subtraction easier:

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

    b. Express the difference **ΔDec** in arcseconds: _____ " (5)

    c. The **ΔDec** will again need to be converted to degrees for use in step e by dividing the **ΔDec**
        in arcsecond by 3600.

        ΔDec_____°

    d. Express the difference **ΔRA** in seconds: _____seconds

    e. Convert to arcseconds by using the equation below. The Declination is the total Dec not the
        difference. It is simply the standard declination of the asteroid. You can use the value from
        any measurement—e.g. table W2— as it need only be to the nearest degree.

        ΔRA(") = ΔRA(sec) x 15 x cosine(Declination°) =_____"

    f. Calculate the total parallax in arcseconds:

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

using ΔRA in arcseconds from step e and ΔDec in arcseconds from step b.

Parallax = _____"   *(15)*

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

Distance to the Asteroid = 206,265(Baseline/Parallax)

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

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

   i.   Distance of 1992JB = _____km.

   ii.   Distance of 1992JB = _____Astronomical Units.   (0.3)

h. Compare these distances with the distance of the Moon, Mars, Asteroid Belt, and Jupiter from Earth. These values can be found on the web.

   i.   Earth to Moon   _____km, _____ AU

   ii.   Earth to Mars   _____km, _____ AU

   iii. Earth to Asteroid Belt _____km, _____ AU

   iv.   Earth to Jupiter   _____km, _____ AU

i. How many times further or closer is the asteroid than the moon? _____.

j. 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. Based on the above, what kind of an asteroid do you think this is? Why?

Part V:

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 step p and the distance in Part 4 step h,i of this exercise. Then it follows that the tangential velocity is represented as:

$$V_t = (μ \text{ x dist.})/206{,}265$$

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

V$_t$ = _____ **km/sec**   *(3)*

QUESTIONS

1. There are two perpendicular components of the velocity of the asteroid. One is the tangential component calculated above. What is the second component? Draw the velocity vectors and label both components.

2. What is the orbital radius of the Earth? What is another name for this distance? Express this distance in both AU and km. Draw a picture of the Earth orbiting the Sun to help you answer this question.

3. What is the orbital period of the Earth? Express this answer in both years and seconds.

4. Using the information from questions 2 and 3, we can calculate the orbital velocity of the Earth for comparison with the orbital velocity of the asteroid. Velocity can be calculated by using this equation: velocity = distance / time. Using the orbital radius of the Earth, divide the circumference of the Earth's orbit ($2 \pi R_{OE}$) with its orbital period (T) in seconds to determine the earth's orbital velocity.

$$V_O = 2 \pi R_{OE} / T$$

5. Would you expect an asteroid to have a lower or higher orbital velocity than the earth? Why? Look at the orbital velocities of planets in our Solar System in an appendix in your text for a pattern on which to base your answer.

6. How does this asteroid's tangential component of velocity compare to the orbital velocity of the earth? Does it follow the pattern of orbital velocities of other objects in the Solar System?

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). Use the worksheet to caluculate the velocity of asteroid 1992 JB. We determined the angular velocity in Part 3 step p and the distance in Part 4 step h,i of this exercise. Then it follows that the tangential velocity is represented as:

$$V_t = (\mu \text{ x dist.})/206,265$$

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

$V_t =$ _____ **km/sec**   *(3)*

FINALLY,

What does this exercise tell us about the difficulty in finding asteroids and the length of time needed to make an accurate estimate of their location?