Name: ______________________

Date: ______________________

Section: ______________________

Astron 104 Laboratory #6
The Size of the Solar System
Section 1.3

In this exercise, we will use actual images of the planet Venus passing in front of the Sun (known as a *transit of Venus*) to determine the size of the Solar System and the distance between the Earth and the Sun (which is defined to be an *Astronomical Unit*).

If you need help running the software, or want more information, please look at:
`ftp://io.cc.gettysburg.edu/pub/clea_products/manuals/Transit_Manual.pdf`

Background

With the establishment of the Sun-centered Copernican planetary system in the 1600's, astronomers were faced with the question of the size of the Solar System. Using observations of Tycho Brahe, Johannes Kepler was able to determine the relative sizes of the orbits of the planets in terms of the distance from the Earth to the Sun, the *Astronomical Unit* (or AU). For instance, they knew that Venus was 0.72 AU from the Sun. But they did not know just how far an AU actually was.

In 1715, Edmund Halley (of Halley's comet fame), first proposed a workable method of determining the Astronomical Unit using observations of transits of Venus. Halley's method involved a time-honored way to measure distances using simple trigonometry. If two observers at different locations on the Earth could simultaneously view Venus as it passed in front of the Sun, a northern observer would see the planet shifted to the south on the face of the sun with respect to what a southern observer would see. This shift, called *parallax*, depends on the distance between the two observers on the Earth.

If the parallax, Θ, is measured, and the *baseline* or distance B, that is the distance between the two observers, is known, then a simple trigonometric formula gives the distance between the Earth and Venus, as shown in Figure 1 below. Once the distance to Venus is known, the length of the Astronomical Unit can be found, since the distances between the Sun and Venus and between the Earth and Venus in Astronomical Units are known.

At the time, this was very hard to do, since precise clocks were not available. Instead they made use of a related method which gave a pretty good result. However, now we have very good clocks, and we can record precise images of transits from many places on the Earth at the same time. We will use actual data to determine the length of the AU.

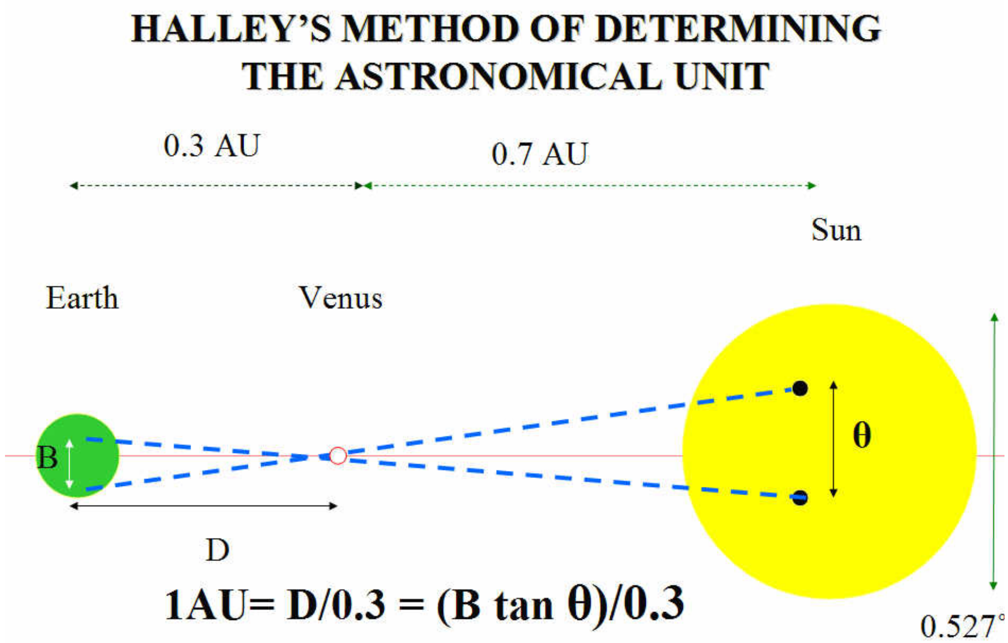

Figure 1: Halley's Method of Determining the Astronomical Unit

Making Observations of Transits using Modern Technology

The ease of the method nowadays a consequence of the fact that it is a simple matter to record digital images of the sun as Venus passes across it. These images can be stored, transmitted over the web, and measured to high precision using computers. Even more important, we can now keep global time far more precisely than was possible in past centuries. GPS receivers and the internet make it possible to synchronize clocks to within a small fraction of a second—so it is no longer necessary to measure the exact durations of the transits and then perform complex calculations to determine the different tracks of Venus across the sun as seen from two sites. Two images taken at exactly the same time—as measured by precisely synchronized clocks—will yield the parallax shift of Venus quite nicely.

What is even more convenient, however, is that we no longer have to travel around the world to set up observing sites in advance of the transit—the telescopes are already in place, pointed at the sun, snapping pictures even as you read this manual. In 1995 astronomers at the National Solar Observatory completed the construction of a global network of telescopes designed to study the sun continuously. The six telescopes in the network are located in Big Bear, California; Mauna Loa, Hawaii; Learmonth, Australia; Udaipur, India; El Teide, Tenerife (The Canary Islands), and Cerro Tololo, Chile. The telescopes are operated by the Global Oscillation Network Group (GONG) based in Tucson, Arizona. Because the Sun is so bright, the telescopes are small, and can be housed in modular trailers, not in the large domes used for telescopes that look at the stars. At least one of the GONG telescopes is looking at the sun at any given time–check out the GONG website at `http://gong.nso.edu` for details about GONG and its telescope sites.

During the transit of June 8, 2004, three of the GONG telescopes were able to observe the passage of Venus across the face of the Sun—the ones in Tenerife, India, and Australia. The locations of these three sites, arranged from the northernmost to the southernmost, are given on Table 1, and their locations are shown on the map in Figure 2, below.

Table 1: GONG Telescopes Used in the June 8, 2004 Transit of Venus

Site	Latitude	Longitude
Observatorio del Teide, Tenerife, Spain	$+28°17.5'$	$-16°29.8'$
Udaipur Solar Observatory, India	$+24°35.1'$	$+73°42.8'$
Learmonth Solar Observatory Australia	$-22°13.2'$	$+114°06.1'$

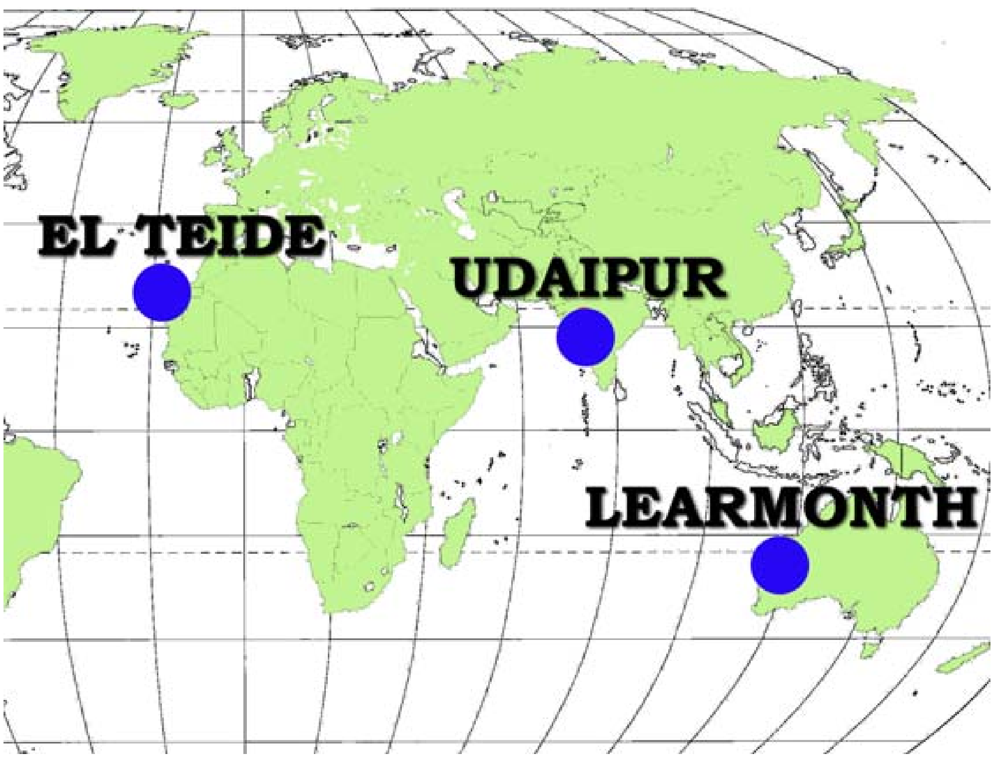

Figure 2: Sites of GONG telescopes that observed the Transit of Venus on June 8, 2004.

Although images are acquired once per minute while the Sun is up at each of the GONG solar telescopes (averaging a total of about 3600 images per day!), the database for this lab includes images that were taken every 5 to 8 minutes on average, which is sufficient for determining the path of Venus across the Sun. The images you have are the real data: see the CLEA manual for more technical information.

Basic Strategy

The CLEA software associated with this exercise allows you to display images of the Sun from the GONG solar telescopes and to measure the positions of the silhouette of a transiting planet.

Your primary task is to compare the tracks of Venus across the sun as seen from a pair of GONG telescopes at two different observing sites and determine the angular shift or parallax, π_m, in seconds of arc, between the two tracks at one particular time. From the value of that angular shift, and the known distance between the two sites, you can then determine the distance between the Earth and Venus. The basic data are the images from the GONG telescopes. From them, you plot two tracks, and from the plot you measure the angular shift. A sketch of the two tracks and the angular distance you will be measuring is shown in Figure 3.

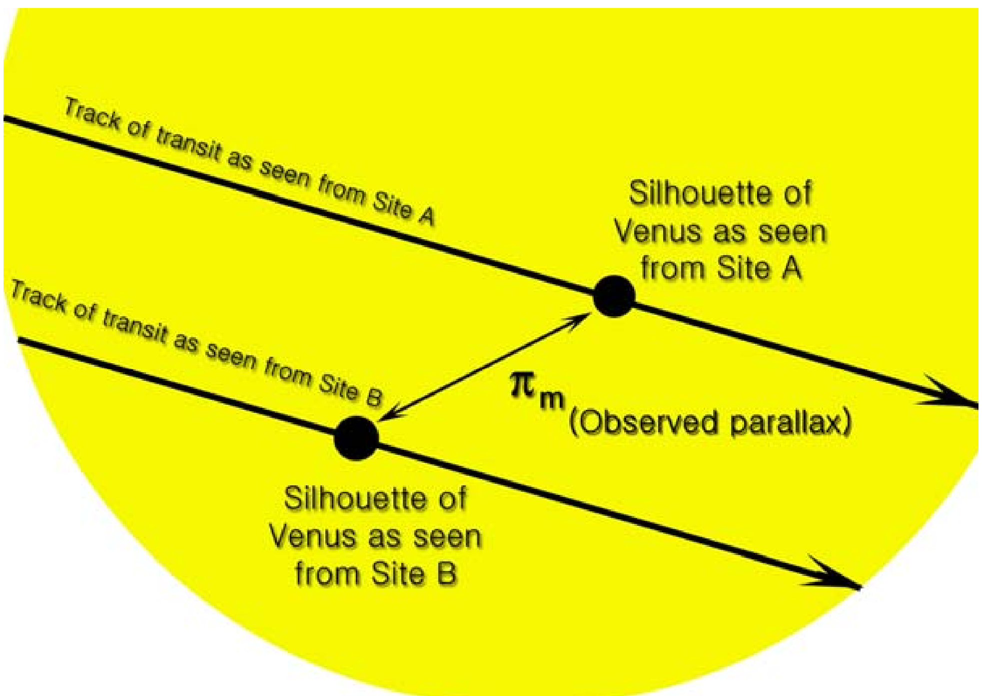

Figure 3: The tracks of Venus across the sun as seen from two sites. Also shown are the appearance of the silhouette of Venus from the two sites as seen at the same time, and the observed parallax of Venus, π_m.

Procedure

1. Run the CLEA *Transits of Venus and Mercury* software. Log in. Choose *File—Run—2004 Venus Transit* and the main data window will appear.

2. Choose *File—Image Database—Image Directory—Load* , and you will see a list of the three GONG observatories that took images of the Transit. We will measure the data from each of these, but let's choose the data from Learmonth first. Double click on the entry for this observatory, and a list of all the images from this site will be loaded into the Image Database Directory column of the main data window. Scroll down the window to see what times are available.

   All the images were taken between these times on June 8, 2005:
   Site: Learmonth
   Images between   and   UT.

3. Select all the images by left-clicking on the Database Directory and choosing *Select All*. Load all these images into the computer by left clicking again and choosing *Load Selected Images*. An image window will open showing each image as it's loaded in. When all the images have loaded you can, if you want, see an animation of the series of images, showing the planet Venus moving across the Sun, by using the *Animation—On* menu on the image window. *Animation—Off* will stop the animation. The animation can be speeded up by changing the *Animation—Set Rate* menu item.

4. You will now measure the position of Venus on each image. To see the first image in the series, make sure the animation is not running (see above), and then go to the top of the Loaded Image List, the left column of the main screen, and left click on it. Venus may not appear on the first few images, so go down through the list until you find the first images where Venus begins to poke on to the edge of the Sun. Continue down the list until you find the image where the complete silhouette of Venus can be seen. This is the first one you will measure. Record the time that this image was taken at.

   What is the time (in UT) of the first image from Learmonth when Venus was visible [**10 pts**]?

5. Next you will begin to measure the positions of Venus on the images. Simply position your cursor over the silhouette of Venus and left click. A window opens showing a magnified image of Venus, and it will automatically center on the planet. Another window opens at the top to show the x and y coordinates of the center in units both of pixels and of fractions of a solar radius. Note: if the magnified view only shows black, then it is too magnified. You can change the magnification by clicking the

"magnification" menu and changing the number; values of 28 to 30 seem to work well. A "measurement data" window will open at the bottom of the screen, showing the same coordinates, time, and information on the observing site. **Very important:** Click the "record" button to add this data to the list of measurements the computer is keeping for you. If you don't do this, you will not be able to analyze your measurements later.

6. Continue on in this fashion through each image taken from Learmonth until all the measurements have been recorded. The software keeps track of which images you have measured, and won't let you record twice (it "grays" out the record button on previously measured images and turns the box around the planet from red to green) so don't worry about measuring the same image twice. If you measure one incorrectly or leave one out, don't worry. Data can be deleted later, and one or two missing image measurements won't affect your final result.

7. When you have finished measuring and recording all the positions from the Learmonth images, save your data. To do this, go back to the main screen, choose the *File—Measurement Data—Save Data* option, give your file a distinctive name (such as your initals or last name), and save it. Record the name here:

8. If you want, you can view the data you've recorded already by choosing (from the main window) *File—Measurement Data—View/Edit*, which will show you a text window with what you've recorded so far. You can also view a graph of your data against a circle representing the sun by choosing *Analysis—Plot/Fit Data*. The graphical window that appears will later be used, when you have all your data, for determining the parallax of Venus. Close these windows before proceeding.

9. Now proceed, **following the steps 2–8 above**, to load in the images from the next GONG site, Udaipur, measure and record the positions of Venus on each of them, and save the results (they all go on to the same data file; you don't have to change the name). **Do not close the image window after entering the data for Learmonth, otherwise the Udaipur data won't load.**

10. When you have finished measuring the images from Udaipur, do the same for the images from El Teide. Note that the last few images from this site will not show complete silhouettes of Venus, so you shouldn't measure them. **Again, don't forget to save the data!**

11. You now want to view and analyze the three tracks. To do this, from the main menu choose the *Analysis—Plot/Fit Data* and you should see the three tracks plotted against a circle representing the sun. Note that they are very close together. The parallax of Venus is quite small. But you can view it in more detail by choosing *View—Detail* from the plot window menu. Note that the three tracks are now well separated. The circles represent the measurements you have recorded.

Why are these three tracks are in the order you see them: Why is the Learmonth track at the top, and the El Teide track at the bottom? (a diagram may help). [**10 pts**]

12. The points you have measured should appear to be connected by straight lines, which gives a jagged appearance to the tracks. Next we need to fit a single line to each track, smoothing out experimental imprecisions. Choose the *Data—Curve Fit—Quadratic* menu option, and you will see single slightly curved lines fit to the data.

13. The shift, or parallax of Venus, π_m , between any two tracks is what we use to determine the length of the Astronomical Unit. It can be measured at any time during the transit, but we will want to measure all three shifts between the three combinations of the three sites (Udaipur vs El Teide, Udaipur vs Learmonth, and Learmonth vs El Teide), so we need to choose a time when the transit is visible from all three sites. To do this, choose *Data—-Select Observation Time* and a slider will appear below the plot. If you slide it back and forth, you will see three circles appear on the tracks that represent the positions of Venus as seen from the three sites at the time set on the slider. Find a time when the transit is visible from all three sites. Click OK to set that time into the computer. A small window opens at the top of the page recording the time and the parallaxes as seen between the three pairs of sites the units of parallax will be in fractions of a solar radius, and will later have to be converted into arc seconds. Record the results [**10 pts each**]:

Observation Time (UT):	
El Teide-Udaipur	**Parallax (Solar Radii)**
El Teide-Learmonth	
Udaipur-Learmonth	

To convert the parallax from solar radii into arcsec (needed below), use:

$$\pi_m\,(\text{arcsec}) = \pi_m\,(\text{solar radii}) \times \text{solar radius}\,(\text{arcsec})$$

14. We need additional information to use in the formula for the length of the Astronomical Unit: the "projected baseline" between any two sites, the distance to the Sun and Venus in Astronomical Units, and the angular size of the sun (to convert the parallaxes to arc seconds.

The computer calculates this information once the observing time is selected. Simply choose *Data—Sun, Planet, Baseline Data* from the plot display window, and another window will open up with all this data. You should now be able to use the data from that table (not all the data it prints out is needed), to fill in your table [**30 pts total**]:

Observation Date and Time (UT):		
Distance of the Sun D_{es} (AU):		
Distance of Venus D_{ev} (AU):		
Apparent Diameter of Sun (arc seconds):		
Apparent Radius of Sun (arc seconds):		
El Teide-Udaipur	**El-Teide Learmonth**	Udaipur-Learmonth
Projected Baseline (km)	*Projected Baseline (km)*	*Projected Baseline (km)*
Parallax π_m (arcsec)	*Parallax π_m (arcsec)*	*Parallax π_m (arcsec)*

15. Now use the data from the table above to calculate the length of the Astronomical Unit using the parallax from each of the three pairs of observing sites and the formula below. Also calculate the average value. [**15 pts total**]

$$AU = \frac{B \times (D_{es} - D_{ev}) \times 206265}{\pi_m \times D_{es} \times D_{ev}}$$

AU is the length of the AU in km, B is the baseline in km, π_m is the measured parallax in arcseconds, and D_{es} and D_{ev} are the distances recorded above.

Length of the AU Determined From Transit Observations (km)	
El Teide-Udaipur	
El Teide-Learmonth	
Udaipur-Learmonth	
AVERAGE	

16. What is the percentage difference between your answer and the currently accepted value of the Astronomical Unit (1.4959787×10^8 km)? [**5 pts**]

Extra Help (if you need it)

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 *Transits of Venus and Mercury* exercise. Position the mouse over the 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 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 *first* name (and partner's name, if applicable). Do not use punctuation marks. Press "Tab" to move to the next text block, or click in each text block to enter the next name. Next enter the Laboratory table number or letter if it is not already filled in for you. Click in appropriate field to correct any errors. 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 *Transits of Venus and Mercury* lab will then appear.

Choosing an Exercise to Run

You will first choose *Run the Exercise* from the *File* menu. Choose the data on the 2004 Venus Transit.

Loading and Displaying Images

When you first run the program you will see a *Main File List* area with two frames, the left labeled *Loaded Image List* and the right labeled *Image Database Directory*. Both will be blank. By using the *File* menu, you can load a database of images taken during the transit from one of the three observing sites (double click with the left mouse button on your choice of site). After you load the image database from the *File* menu, you will see a list of the available GONG images, ordered by Universal Time of the image, in the *Image Database* window. Images can be selected singly or the entire set can be selected. You can load and display an image in one of two ways. You can right-click on the image data box which will give you a set of selection and display choices. Or you can use the *File* menu. Once you load an image, its date is also displayed in the list of *Loaded Images*. The last-selected image is automatically displayed in a large popup *Image Display Window*.

For this exercise we suggest you "select all images" and then load them. It may take a minute or so for them all to load, and while they are loading you will see them appear one by one in a display window on your screen while a window displays the progress of the load (the percentage of files loaded). When all files have loaded, click the OK button on the window which has been listing the progress of the load.

You can display any of the images in the *Loaded Image List* window by double clicking on the image time. (You can also use the right mouse button to bring up a pop- up menu that will allow you to display the image, remove it, or remove all the images currently loaded).

Measuring the Positions of the Silhouette of the Transiting Planet

The most notable feature on all the images is the silhouette of Venus or Mercury (except for those near the very beginning or end of a series, when the planet has not yet moved in front of the Sun). In order to plot the track of the planet across the Sun you need to measure the position of this silhouette on every image of the series. It's a bit tedious, but the software makes it very easy.

The image display permits you to measure the positions of points on the image, and it will automatically measure the coordinates of the center of the silhouette. To start measuring silhouette positions, start at the top of the *Loaded Image List*, and by left clicking on each image date one by one, find the first one on which the entire silhouette appears. (The first few may not show the silhouette, or may only show part of it).

To measure you need only left click on the displayed image, or you can choose *File—Image—Measure* from the menu bar at the top of the image display. A small window will appear with digits to indicate the position of the cursor in *pixels* and in *solar radii* (fractions of the apparent radius of the Sun). The position of the cursor is updated whenever you click the left mouse button, or continuously if you hold the button down. You will also see a small magnification window that shows the area around the cursor. Pixels are of course just the little blocks that make up the picture, and pixel 0,0 is right in the center of the image.

Recording Data

When you are measuring silhouette positions, there will be a small window on the screen (usually at the lower left) labeled *Measurement Data*. When you click the "record" button, the image date and time and the position of the cursor are written to a data file, and the square around the image of the planet turns from red to green. If your instructor has turned on the "automatic centroiding" feature, which is usually the case, the software will calculate the precise center of the silhouette beneath the cursor when you click the right mouse button. (If the automatic centroiding feature is not turned on, place the cursor as close to the center of the spot as possible before recording the position.) The small magnification window helps by giving a magnified view of where the cursor is pointing, and the amount of magnification can be set, if desired, using a menu on the magnification window. The computer remembers whether you've measured a particular image, and will not let you measure it twice. (But see the next section to find out how to delete erroneous data).

Seeing Tables and Plots of Recorded Data

At any time after you have some data recorded, you can view all the recorded data in a separate *Transit Measurements* window. To do this, go back to the Main File List window and choose *File—Measurement Data* from the main menu bar. There are choices that let you view the current data, or load a file of previously saved data. If you choose to view the list, you will see the data window appear on the screen. The columns are labeled; the observing site is at the top, and the x and y position of the center of the planet on each image is given in units of fractions of a solar radius . In addition to the date and time of the observation, the window will list the *Julian Date* of the observation, which is a running day number and fraction that is convenient for keeping track of astronomical times. Instead of having to remember the number of days in a particular month when subtracting one date from another, you simply subtract one Julian Date number from another to get the number of days between two observations. A Julian Date begins at Noon, Universal Time; 0.5 day, of course, is 12 hours; each 0.0001 day is about 8 seconds.

You cannot edit individual measurements, since they were made automatically when you clicked on the image on a picture; but if an entry seems to be in error, you can delete it by selecting the line (with a left click of the mouse), and using the *Edit* menu on the menu bar to select *Delete Selected Line*.

It is also possible to view the measurements you are making in graphical form, against a circular image of the sun. Simply drag on the *Analysis* item menu bar on the main window and select *Plot/Fit Data*. A window will open showing a plot showing your position measurements as small circles, connected by straight lines to represent the track of the planet across the face of the sun. The *View* choice on the menu bar of this window will allow you to see the track on the scale of the whole sun, or a magnified view. The magnified view is especially useful when comparing the tracks as seen from two or three sites, because the difference between the tracks is small and can best be seen when magnified.

Measuring tracks from a second and third site

You will want to measure the transit tracks from all three sites. To view the images from another site, just go back to the main window, *File—Image Database—Image Directory—Load* choice and double click on the listing for a different site. Select all the images from this site, and display and measure as you did for the first. Data will be added to the same data list you started for the first site, with new entries labeled as being from the second site. And you can now view the plots of both tracks on the graphical display window, either on the scale of the full solar disk or as magnified "detail" view.

Measuring the Parallax between the tracks and Computing baseline and Distance Data.

Once you have measured the tracks of the transit from at least two sites, you are ready to measure the parallax of Venus as seen from the two sites. Basically, all you need to do is select a time when Venus was visible from both sites, and the computer will compute the angular difference between the two tracks. If it is not already open, open the *Analysis—Plot/Fit Data* window. Then on the plot window select *View—Detail* so you can see the plots more easily. The computer connects your measured observations from a given site with a line to produce a track across the sun from each site—you can select either best fit straight lines or a parabola (quadratic) using the *Data—Fit* menu on the plot window. Then select a time to calculate the parallax by using the *Data—Select Observation time* menu item. A slider will appear at the bottom of the screen, and as you move it back and forth you can see somewhat larger circles appear on the tracks which mark the position of the silhouette of the planet as seen from each site. Pick a time in the middle of the observation period when the planet is visible from all the sites.

Once the observation time has been set, a you can now read out all the information you need simply use the *Data—Sun,Planet,Baseline Data* choice on the plot window, and you will get a window called the Transit Analysis Ephemeris and Baseline Report listing all the information you need to insert into the formula for the Astronomical Unit:

- The “Measured Parallax” in solar radii at the time of observation, which is essentially the distance between selected tracks as seen from a particular two sites. You will need to convert that into seconds of arc using:
- The apparent diameter of the Sun at the time of the observation, measured in arcseconds (this is twice the solar radius, of course).
- The distance from the Earth to Venus, D_{ev} at the time of observation, in AU.
- The distance from the Earth to the Sun, D_{es} at the time of observation, in AU.
- The “Projected Baseline”, the distance between the two sites perpendicular to the direction to the Sun, measured in km (note that miles are also given, but you want km).
- There is also additional information used by the computer, but that you don’t need, such as the coordinates of the center of the sun and the planet, the apparent diameter of Venus, and the latitude and longitude of the observing sites.