Lab Manual for 12.410J-8.287J

by
Susan Kern & Jim Elliot

Contributors: Jane Connor, Wen-fai Fong, John Fregeau, Katheryn Decker French
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Preface

This lab manual explains the procedures that you will need to carry out your project in 8.287J-12.410J, Observational Techniques of Optical Astronomy. These procedures include the preparation of star charts ("finder charts"), how to find objects with the telescopes at Wallace Observatory, instructions for using the instruments and corresponding software to record astronomical data, and directions for using the course software to reduce the data. This manual includes several "tutorials," which give step-by-step instructions for the described procedures, with samples of the results that you should be getting with each step. These should enable you to carry out the procedure—and simple variations of the procedure—on your own. Although some explanations of the general principles behind each procedure are given, the principles are explained in the course notes and in the lectures. Some sections of the lab manual have an exercise that follows the tutorial, which gives you an opportunity to test yourself. Finally, we have included some Appendices with reference material that you may find useful.

Be aware, however, that software and the observatory equipment continually changes, and keeping this manual up to date is a challenge! If something does not work as explained herein, first carefully check that you have followed the instructions to the letter. If you still have the problem, report it to the teaching staff. If the resolution of the problem calls for a correction or other revision to this manual, send it to Professor Elliot (jle@mit.edu) to spare future students from having the problem that you experienced. Happy observing!

You should bring this manual to each lab section.

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1 Constructing a Star Chart ("Finder Chart")

To identify objects while working at the telescope you will need a star chart, which is commonly called a "finder chart" in astronomical work. It is absolutely essential to have good finder charts when trying to locate an object in the sky at the observatory. The pointing accuracy of the manual-slew telescopes is nowhere near good enough to simply dial in the correct coordinates and expect to be pointing at the correct object, unless perhaps your object is the moon. The pointing accuracy of the more automated telescopes can be quite good, if properly calibrated, yet it is still necessary to create a finder chart so you can confirm that the telescope pointed correctly. It's stomach-dropping to realize, several days later when reducing data, that you took 7 hours of data in finger-numbing 15° F weather on the wrong object, which was only 15 arc minutes from the correct object!

Here we describe how to make a finder chart in three different ways: (1) with a program called *Starry Night Pro*, (available on the Macs in the astronomy lab in 37-292, the Lindgren Library, and at Wallace Observatory) (2) with a program called *XEphem*, (provided by Athena), and (3) with the VizieR online catalog, which runs on any computer with an internet connection and Java Runtime environment. The similarities and differences are outlined below.

Both *Starry Night Pro* and *XEphem* are excellent programs to make simple finder charts. *Starry Night Pro* is useful for constructing star charts of well-known objects quickly and clearly because you can save certain attributes such as the location of Wallace Observatory, the field of view (FOV) finderscope, eyepiece, and CCD, so you do not need to reset them the next time you use *Starry Night*, provided that you use the same computer.

XEphem is great for constructing slightly more detailed finder charts because the program has a lot of unique features. First, it can invert any star chart you construct to match the simulate the mirror-flipping of the image in the telescope. It also allows you to download any catalog of celestial objects available online, so you may construct finder charts for fainter or newly discovered objects. Lastly, it runs on Athena allowing you access it from any cluster on campus. However, this also means that you need to reset attributes, such as the location of Wallace and the eyepiece FOV, every time you use the program, which may take extra time. Both *Starry Night Pro* and *XEphem* have a feature that obtains target information from online databases that are updated daily. However, the databases are limited, and consequently, these programs cannot display lesser-known objects, such as 16^{th} magnitude stars.

The *VizieR* online service is a compilation of many star catalogs and is very useful for making detailed finder charts. *VizieR* will even display stars whose magnitudes are well beyond the detecting capabilities of the shed telescopes at Wallace. However, if your object is faint, it is always a good idea to supplement your simple finder charts with more detailed ones in case the night is particularly clear and your *Starry Night* chart is not sufficient. See Appendix C for the link to the *VizieR* website.

1.1 Starry Night Pro (available on select Macs in the lab and libraries)

Starry Night Pro is the primary program that we support for making finder charts and planning your observations. It resides on the Macintosh computers the astronomy lab, the Lindgren Library, in the main building at Wallace Observatory. You can download a trial version for your own computer at the URL `http://www.starrynight.com/digitaldownload/trial_download.php` if you are interested. Here we explore some common tasks one might use this program to accomplish. The program has many more capabilities than those described below, and the teaching staff encourages you to explore these additional features on your own.

Starry Night is primarily used to synthesize what you expect to see at the telescope before you are actually there. For example, if you want to observe the Andromeda Galaxy from Wallace during your lab section, you can create a chart that will allow you to determine (1) if the Andromeda Galaxy is above the horizon during your lab section and (2) how to find it in the sky. To do this, you can simulate your expected observing situation by setting the conditions on *Starry Night* accordingly. To do this you need to set your location on Earth and the time you expect to be looking at the sky. You will also want to know how to find and center an object on your screen in the simulated sky once you are situated.

When you launch *Starry Night*, you may see something similar to the window displayed in Figure 1:

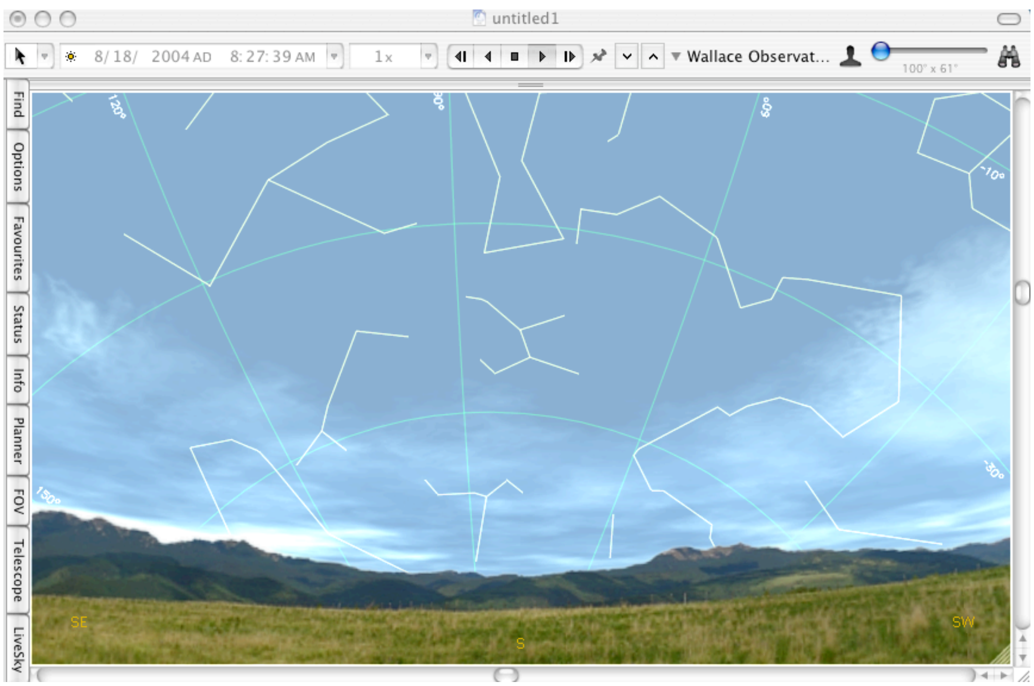


Figure 1. Sample of Starry Night main screen upon launch. See text for description of program.

In order to move around and execute commands in *Starry Night*, the cursor must be appropriately defined. The box in the top left-most corner (it has an arrow in the picture above) allows you to change the cursor functions as you move around within the program: adaptive (chooses one of the following cursors depending on what the program thinks you want to do) – angular separation (find the angular separation in the sky between two objects) – arrow (for selecting objects in the display) – constellation selector (select the nearest constellation to where you click in the display) – hand (scrolling in the display)– QTVR tracker – location scroller (change your location on Earth as you scroll) – magnification (zoom in and out).

1) Set the location: To the top right in the above image you should see the words "Wallace Observatory". You can change your location by clicking on this pull-down menu and scrolling down to "Viewing Locations—Other". Once here, you can set your location by (a) selecting a location from the list, (b) selecting the "map" tab, then clicking on the map, or (c) selecting the "latitude/longitude" tab and typing in the latitude and longitude of where you want to be (for Wallace this is: +42° 36.6' N, 71°29.1' W).

2) Set the Date/Time: The date and time is defaulted to be "now" when you first open the program. You can change the time by clicking on the pulling down and selecting one of the options, or by clicking on the part of the day or time you want to change and simply typing your new values with the keyboard.

   i) The button next to the time that reads "1x" can be modified to any time increment you desire via the pull down menu to the right of the number. For example, you might speed up time to see what will happen to your object over the course of a night, or to see when the moon comes up in comparison to your object.

   ii) Time can be run forwards or backwards with the five buttons to the right of the time increment.

3) Find an object and center it in the chart: On the left hand side of the screen (Figure 2) there are a series of menus (find – options – favorites – status – info – planner – FOV – telescope – livesky). Click on "find" and the tab bar will slide open. Type the name of the object you want to find in the box at the top and press enter. A list of possible matches to your inquiry will be displayed below where you typed. To center one of these objects, click on the arrow to the left of the name and scroll down to "Centre". Your object will then be centered on the screen. If your object of interest is below the horizon you will be asked if you want to reset the time to the "best time" – this is defined to be the point at which the object is highest in the sky – or "hide horizon". Select one of these. You can zoom in on your object by sliding the bar on the top right of the display where the little pair of binoculars is located.

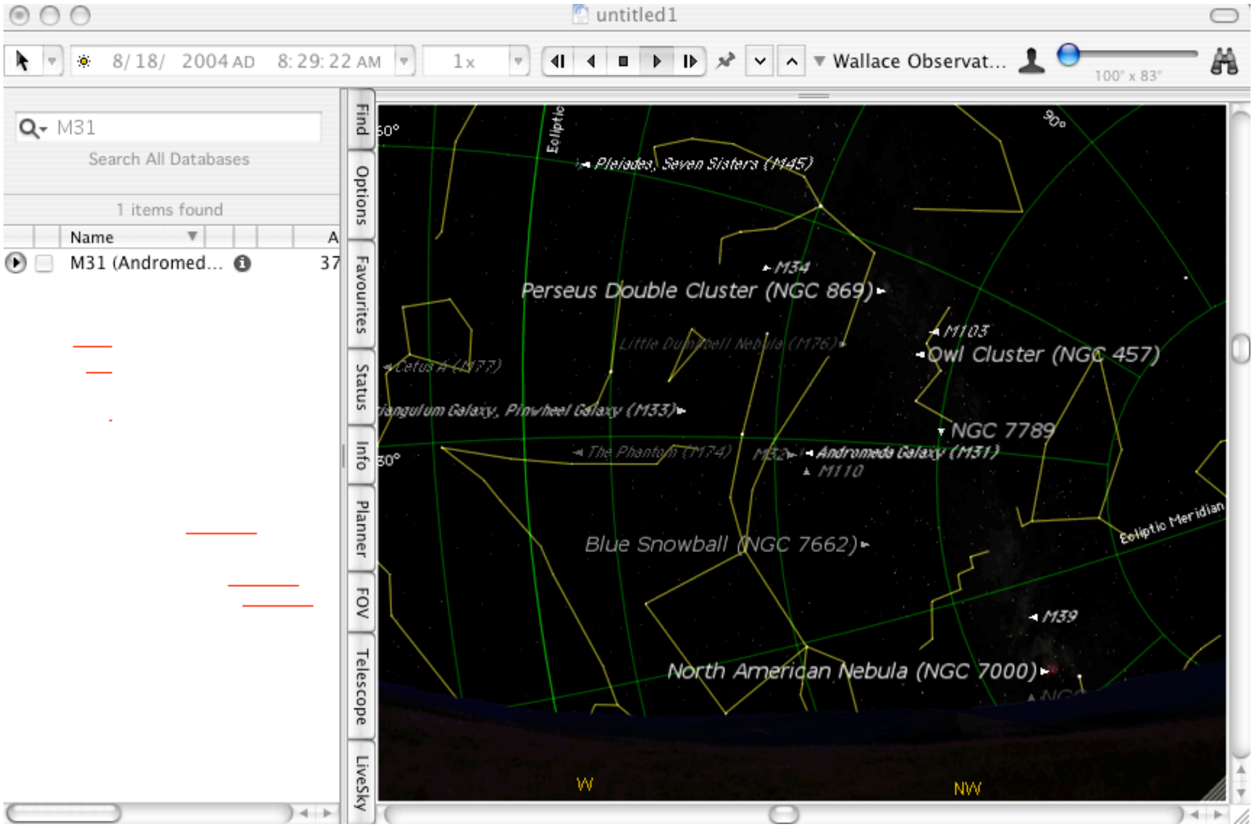


Figure 2. Sample of Starry Night screen to search for and center on the Andromeda Galaxy, M31. See text for how to create this screen.

If you want to get information about your object of interest, click the "info" tab below the "find" tab. Information relevant to the object's observational circumstances are displayed in addition to a brief description about the object itself.

There are various other menus and tabs (Figure 3) that allow you to set viewing parameters (coordinate systems, constellation overlays etc.) and to get other information relevant to your object or field. You are encouraged to explore these on your own.

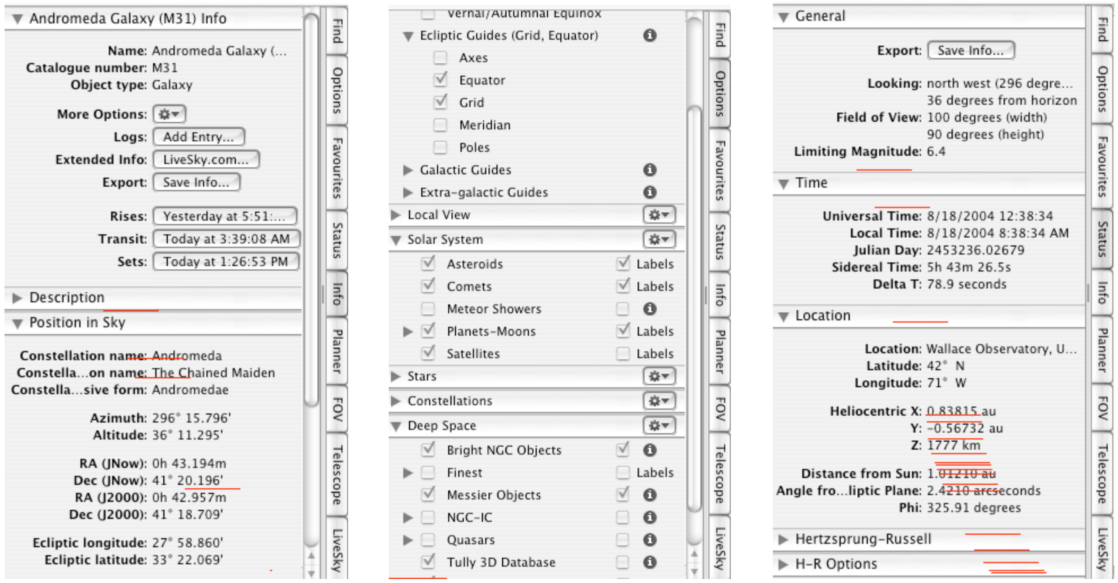


Figure 3. Sample of Starry Night tab menus of interest (left to right): Info, Options and Status. See text or Starry Night help for additional information on the contents of these tabs.

If you want to find an object by its coordinates rather than its name, click on the "edit" menu and scroll down to "center on...". A dialog box will appear where you can type in the coordinates of your object.

You may also want to overlay field of view (FOV) boxes on the display to determine what stars you should expect to observe through the finderscope (Figure 4), the main telescope eyepiece, or the CCD (charge-coupled device, for more information see section 3). Click on the `FOV` tab and checking the box next to the FOV(s) of interest. More than one box can be displayed at a time. You can define new FOVs here as well if the one you want is not already in the database.

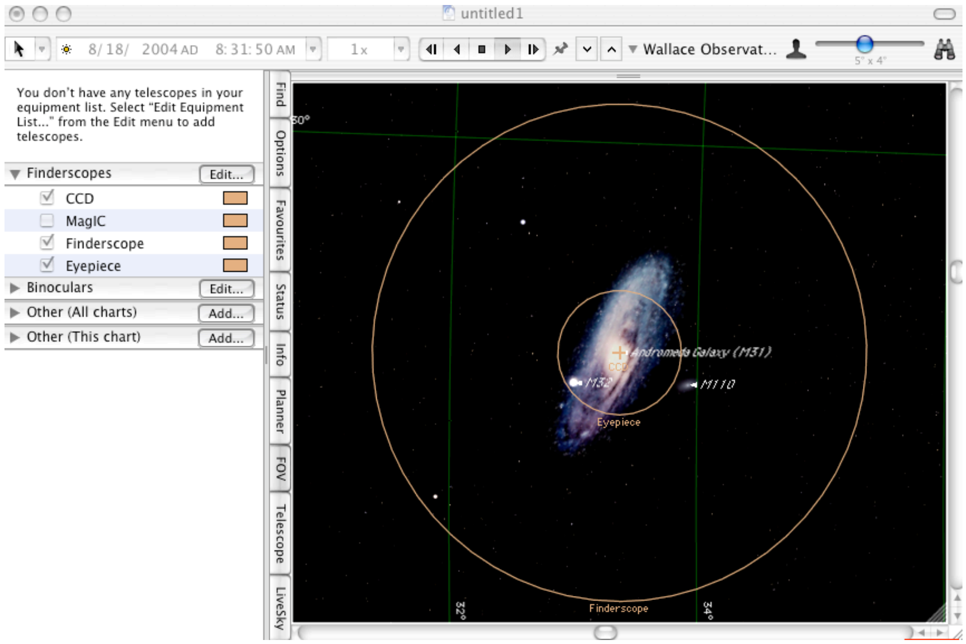


Figure 4. Sample of Starry Night screen for FOV overlay of finderscope, eyepiece and CCD on a region of sky over the object of interest, in this case, the Andromeda Galaxy, M31. See text for how to create these overlays.

To print a copy of your finder chart go to the "file" menu and scroll down to "print" (Figure 5). You can either print to the printer directly or print to a .pdf file. The file will print black stars on white so as not to waste black ink. The printout will cover the area visible on your computer screen plus a little more of the surrounding sky.

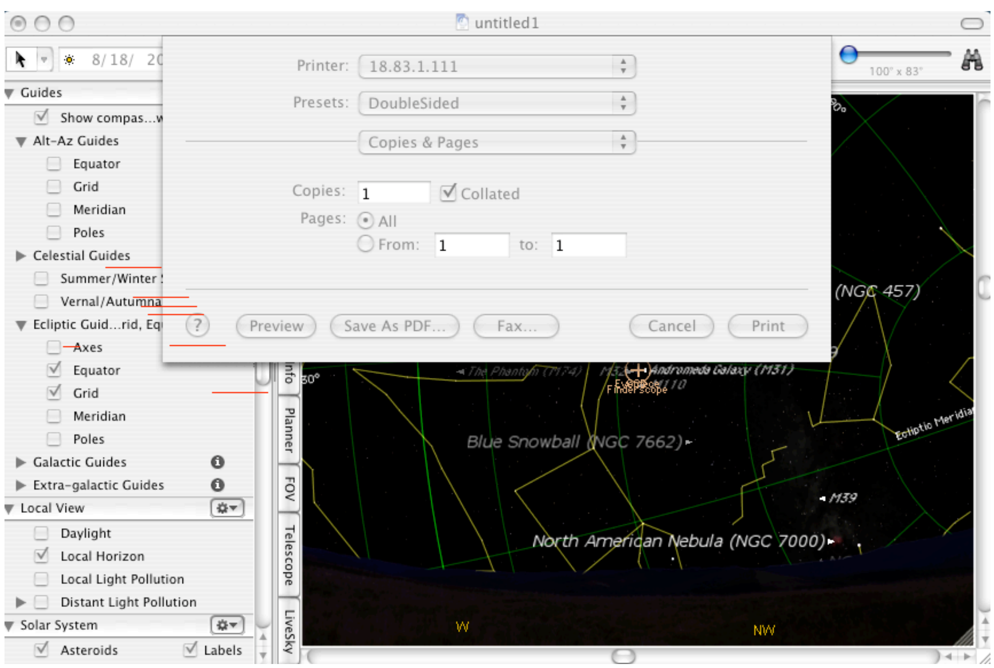


Figure 5. Sample of Starry Night screen for printing. Select "`save as PDF`" to save to a file.

1.2 Xephem (Athena computers)

XEphem is an excellent, free ephemeris program that can be used to simulate sky views, create and print finder charts, and do just about everything you need to do to prepare for your observations in this class. You can find more information about *XEphem*, and download it, at the *XEphem* website (`http://www.clearskyinstitute.com/xephem/`). *XEphem* runs on UNIX (e.g., Linux and Mac OS X), but not Windows. It is already installed on Athena.

This tutorial describes how to run *XEphem* on Athena, configure it, view the sky, locate objects, load catalogs, and create finder charts. It was written when version 3.5.2 of *XEphem* was current. If you are using a different version, some of the details presented here may differ, although the general principles should be the same.

1.2.1 Starting *XEphem* on Athena

Login to Athena. If you are on a non-Athena UNIX computer, access Athena with `ssh`:

```
ssh -X username@x.dialup.mit.edu
```

where "username" is your Athena username. You will be prompted for your password. If your local *SSH* is so configured (and it probably is), graphical programs started on Athena (such as *XEphem*) will display on your local machine.

XEphem is in the "`xephem`" locker on Athena. To add the locker, type the following at a command prompt

```
athena% add xephem
```

This will attach the filesystem containing *XEphem* and allow you to run it. To run it, type

```
athena% xephem
```

at the command prompt. If the latest version of *XEphem* hasn't yet been compiled for the architecture you are running on (and it very well may not be), you will receive a warning, and will have to run an older version, such as "xephem-3.4". As of August 2008, both standard Linux and Sun Athena platforms had working versions of XEphem.

A window similar to Figure 6 should appear on your screen (left panel):

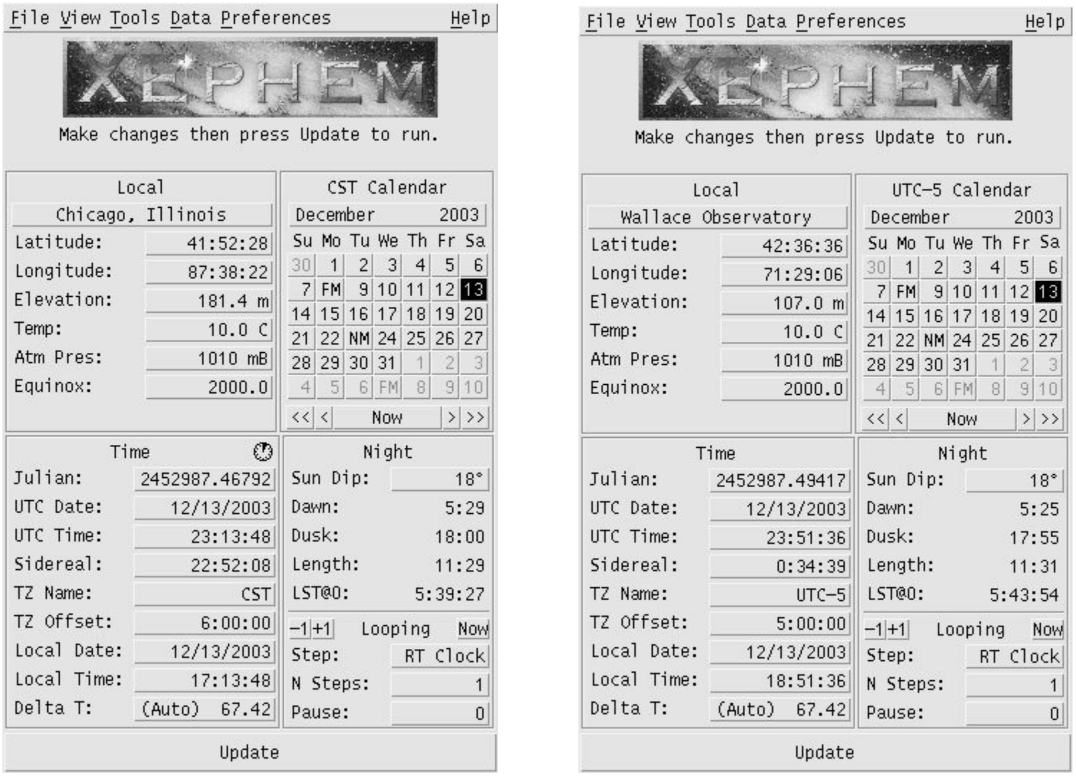


Figure 6. *XEphem* location, time and date window. The left panel shows the main *XEphem* window with its default location set for Chicago, Illinois. The right panel shows the main window updated for our use with the location set to Wallace Observatory.

1.2.2 Setting Your Location

So that *XEphem* will produce the appropriate sky views, you must give it your observing location and the appropriate time of your observations. This information needs to be entered in the "Local" pane of the main window, as shown in the upper left corner of the panels above.

Wallace is unfortunately not in *XEphem*'s list of observatories, so you will have to enter its information manually. To do this:

1. Set each variable in the "`Local`" pane by clicking on the values and manually entering them. The latitude and longitude of Wallace are +42°36'36"N and -71°29'06"E, respectively. The elevation is 107m.
2. Save the name of the custom-defined location by clicking on the location button.
3. Edit the text.
4. Click the "`Set`" button on the left, and then click "`Close`".

After setting the values, and optionally naming your location, your window should look like the image on the right-hand panel above.

Once you close the window that saves the information you have entered, *Xephem* will flash the words "`NEW CIRCUMSTANCES`" near the top of the window until you click the "`Update`" button at the bottom. This button tells *XEphem* to use the values that were just changed.

You can set the date and time to any value (not just the current date and time) in the upper right and lower left panes respectively. This is helpful for creating finder charts for planning future observations and is particularly useful for planning observations of asteroids, which can move several arcminutes per night. You should also be sure to set your timezone in the lower left panel.

1.2.3 Turning on Field Stars

XEphem comes with a fairly small catalog, including only very bright stars, planets, and some other bright objects. To do serious observing, you need to know the locations of relatively dim stars near your target object. The Hubble Guide Star Catalog (GSC) contains approximately 19 million stars in the magnitude range 6 to 15. As you can imagine, the catalog is quite large in file size. *XEphem* can be configured to download from the web only the GSC stars in the region of interest. This is convenient, because it requires downloading information for just a few stars, instead of the whole catalog. On the other hand, it requires being connected to the web when using *XEphem*. To configure *XEphem* to download GSC stars (Figure 7), from the main *XEphem* window:

1. Go to "`Data -> Configure Field stars...`". A dialog window should open.
2. Check the box labeled "`Internet to xephemdbd`"
3. Click "`Ok`"

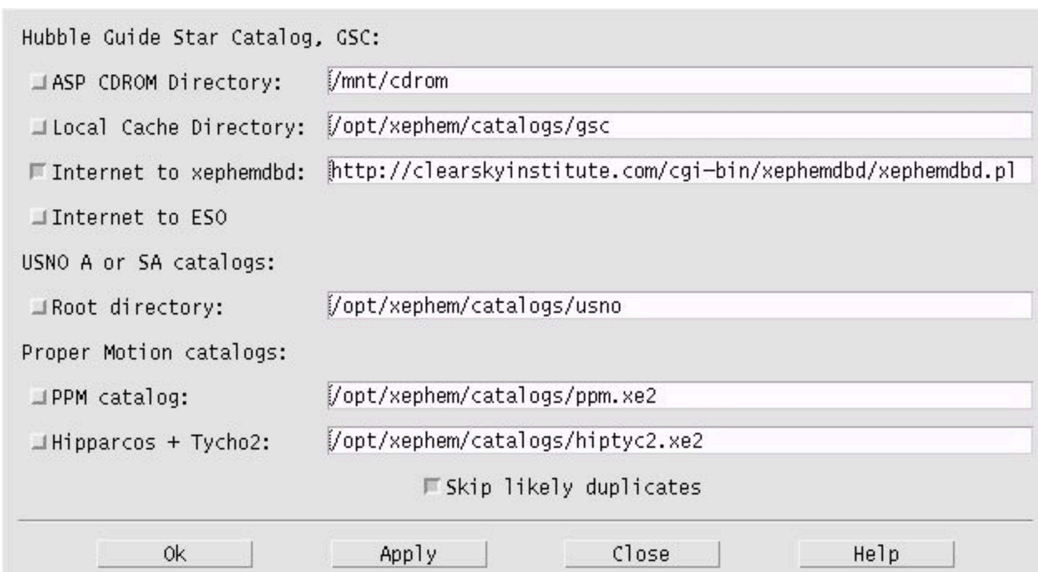


Figure 7. *XEphem* window for source locations of star catalogs. See text for details of how to modify these catalogs.

1.2.4 Viewing the Sky

From the main window (Figure 8), go to "`View -> Sky View...`", and a new window should appear:

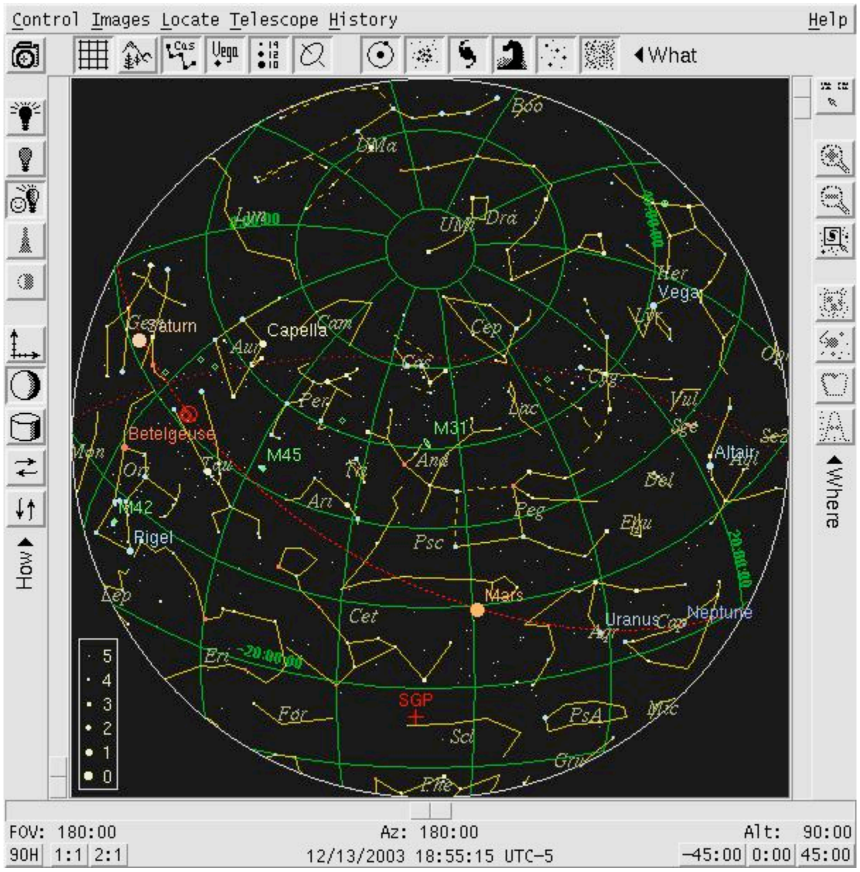


Figure 8. Sample of *XEphem* screen of sky view on startup. See text for description of the side menus and their intended uses.

The slider on the left will zoom in or out, decreasing or increasing the field of view. As you zoom in, a small dialog window will pop up that reads "`Press stop to cancel...`" as it downloads GSC star information from the web. The sliders on the right and bottom will change where you are pointed in the sky in either ALT–AZ or RA–DEC coordinates. To switch between ALT-AZ and RA-DEC modes, click on the box on the left that looks like two axes. The light bulb buttons on the left will adjust the magnitude range of stars shown in the field of view. The left–right arrow and up–down arrow buttons will flip the image along the vertical and horizontal axes respectively.

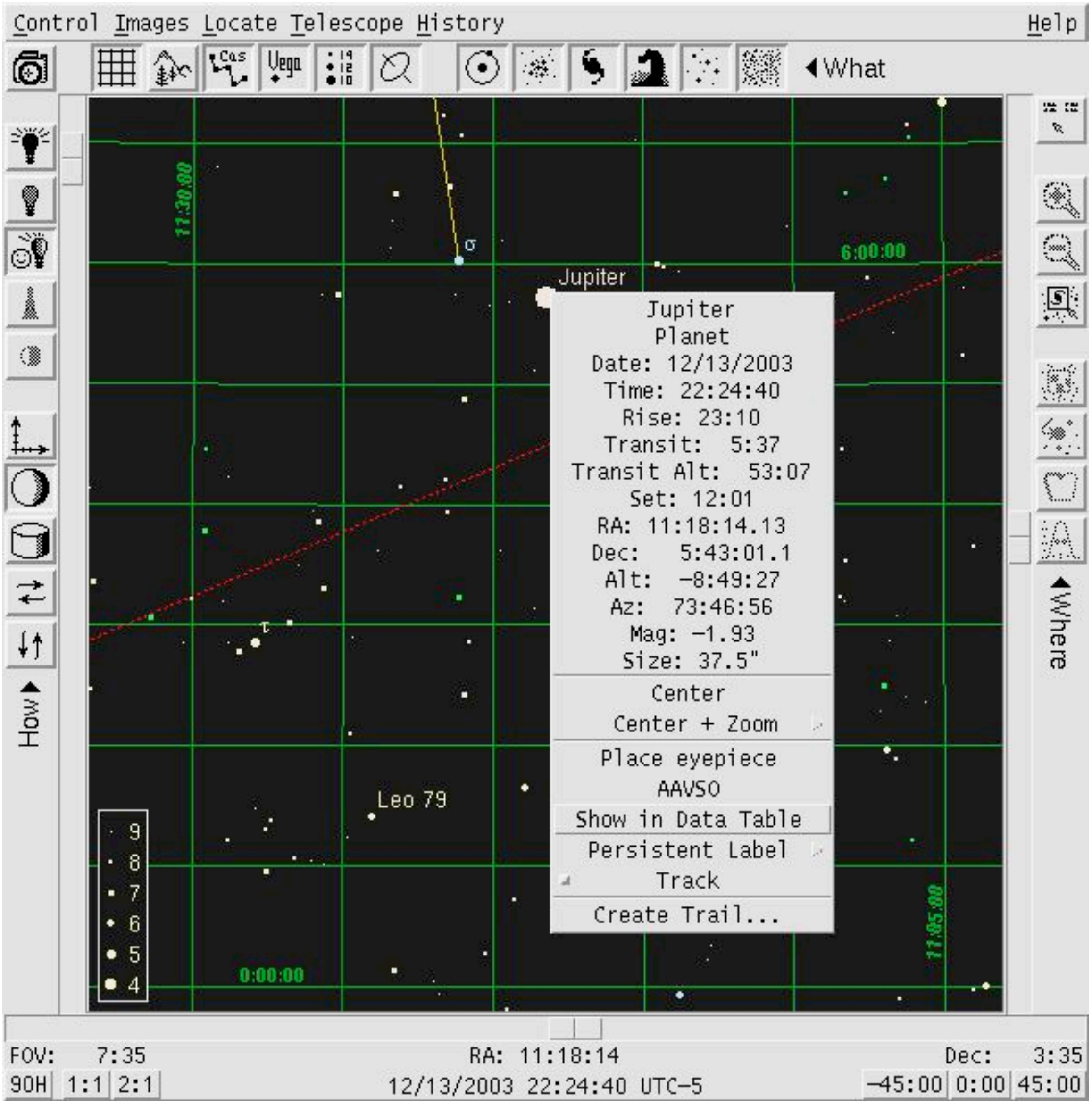


Figure 9. Sample of *XEphem* screen for display of object selection and object information. Right-click on any object to get the displayed information for that object.

Right-clicking on an object will give you information about it (Figure 9), including its name, what type of object it is (e.g., star, planet, space station), when it rises, when it transits, its altitude at transit, when it sets, its RA and DEC, ALT and AZ, magnitude, etc.

1.2.5 Locating an Object

To locate a particular object in the sky view, go to the main window, and select "`Data -> Search memory, define ObjX,Y,Z...`". You should see a window simliar to that found in Figure 10.

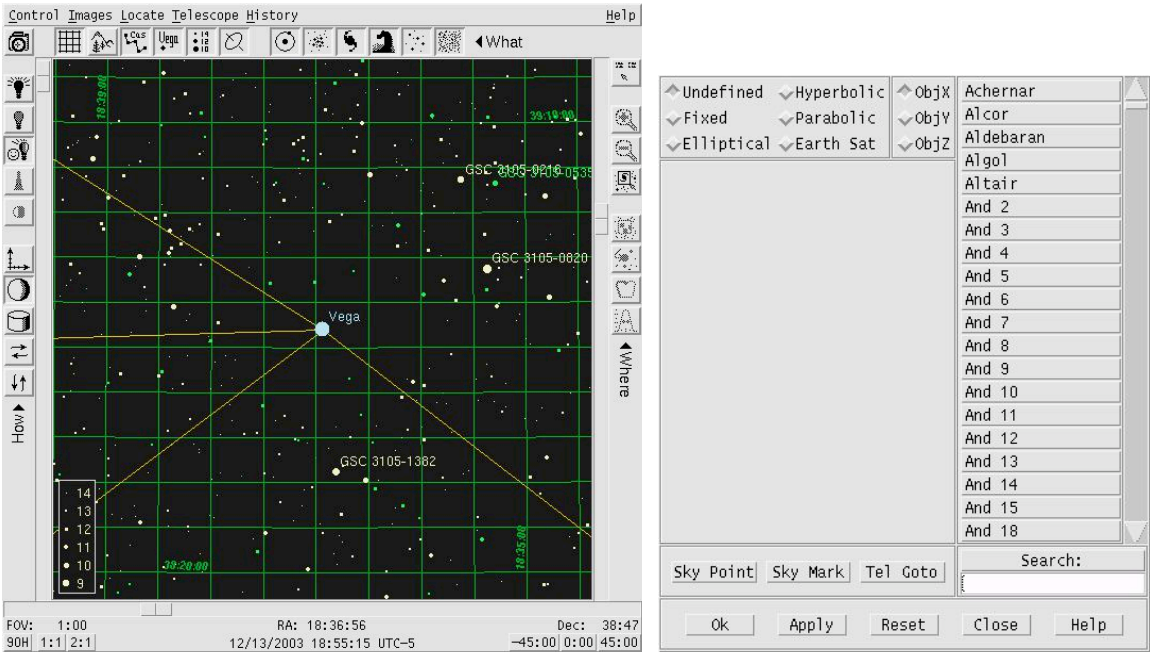


Figure 10. Sample of *XEphem* screen for locating an object (left) and the sky view screen after you have selected and centered on that object (right). See text for more details.

The list of objects on the right of the rightmost image above represents all objects *XEphem* currently has loaded into memory. You can either scroll through the list, or use the search box beneath the list. Once you select an object, click on "`Sky Point`" to center the sky view on that object. Make sure you are zoomed in and that the object of interest is not already in the field of view. Otherwise the sky point command will not do anything. For example, the sky view of Vega might look something like the left-hand panel above after you have clicked on "`Sky point`".

As you can see from the lower left of the starfield, where it says "`FOV`", the field of view for this sky view is 1°. There are many stars in this field of view. By default, some of the brighter stars are labeled, e.g., GSC 3105-1382, however, this parameter can be user defined.

1.2.6 Adding Catalogs

So far, *XEphem* should only have its small default catalog loaded, and should be configured to download the field stars it needs from the GSC. If the object you are interested in observing is not in these catalogs, then you will need to download and load the catalog containing your object. For example, if you are observing an asteroid, you can tell *XEphem* to download the latest updated asteroid catalog from either Lowell Observatory or the Minor Planet Center. In the main window, go to "`Data -> Download Internet files...`". A window similar to that found in Figure 11 should appear.

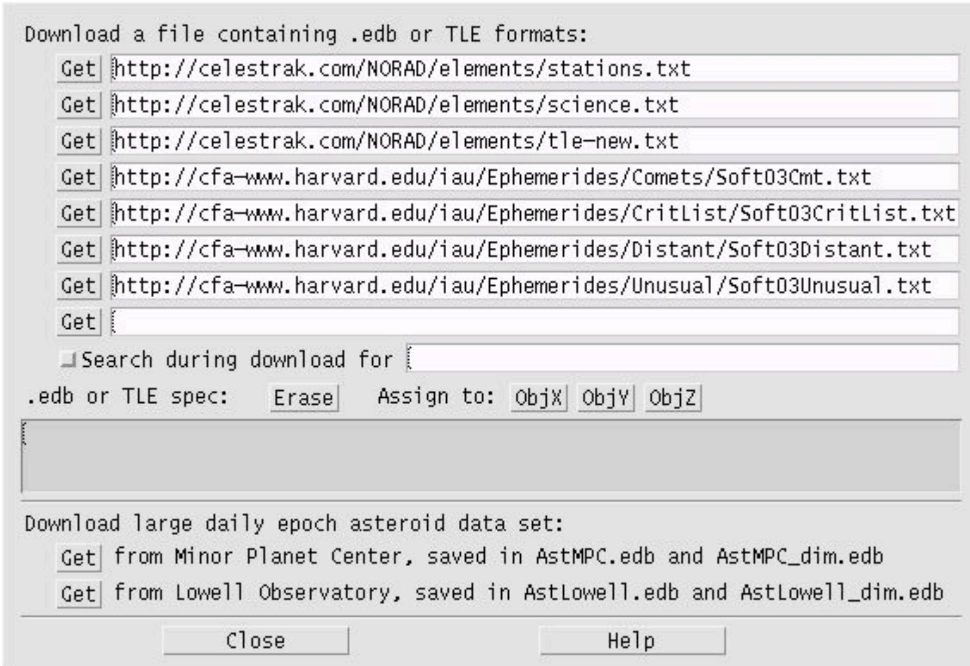


Figure 11. ***XEphem*** **screen for adding star and moving object catalogs. See text for how to modify these catalogs.**

Clicking on the "Get" buttons on the left will download the corresponding catalogs. You can even download a catalog of space stations! The two buttons near the bottom will download and compile asteroid catalogs. However, to use these, you need to have two supporting file already on your machine, "`astorb2edb.pl`" and/or "`mpcorb2edb.pl`" and defined in your path. If you don't have them, do a Google search to find them on the web, download and:

1. make them executable:
   `chmod u+x astorb2edb.pl mpcorb2edb.pl`
2. put them in your path
   `mv astorb2edb.pl mpcorb2edb.pl ~/bin/`
3. The last step assumes "`/mit/username/bin`" is in your path. It may not be unless you put it there manually. To do so, put the following line in your ".cshrc.mine" file in your home directory:
   `set path=($path /mit/username/bin)`
   where "`username`" is your Athena username.
4. Log out and log back in for the changes to take effect.

If you are confused by the steps above, Athena help should be referenced for clarification.

After you download a new catalog, you need to tell *XEphem* to load it into memory. To do this, in the main window, go to "`Data -> Load/Delete local files...`". A new window should appear showing a list of the types of objects already loaded, the names of the catalogs loaded, and a button for choosing other files near the bottom of the screen for the catalog file you are attempting to load. The two buttons on the bottom right, "`Shared Dir`" and "`Private Dir`", take you to the system default *XEphem* data directory, and your private *XEphem* data directory, respectively. If you have downloaded any of the catalogs above, such as an asteroid catalog, they will be in your private directory, and will be shown in the file chooser once you click on "`Private Dir`".

1.2.7 Making Finder Charts

Before creating a finder chart, it is important to keep a few key points in mind. First, the telescopes at Wallace are equatorially mounted, and the CCDs mounted on them are aligned with the equator. This means that the vertical axis in a CCD frame is aligned with declination, and the horizontal axis is aligned with right ascension. Therefore, if you create your finder charts with RA-DEC alignment, it will reduce one unknown when you are trying to match up stars seen in the CCD with stars on the finder chart, namely the rotation angle. Second, the view through the eyepiece of a telescope is the mirror image of the view with the naked eye. The CCD image may also be mirror flipped with respect to the eyepiece view. Therefore, it is useful to create finder charts with all four possible mirror flips. Third, it is vital to know the scale of what you're looking at through the finder scope, the eyepiece, and the CCD. The dimensions for all of these are listed on the Wallace website and in Appendix B. You can use these dimensions to draw the appropriate circles and rectangles representing these views and overlay them on the sky view and your printed charts. Fourth, finder charts should show the sky as it will appear at the date of time of your observation. You should change the date and time on *XEphem* in the main window to match those of when you will be observing, and then click on "Update".

XEphem can store and use several eyepieces at a time. To define an eyepiece, in the sky view, go to "`Control -> Eyepieces...`". You will see a window that looks like the panel on the left of Figure 12:

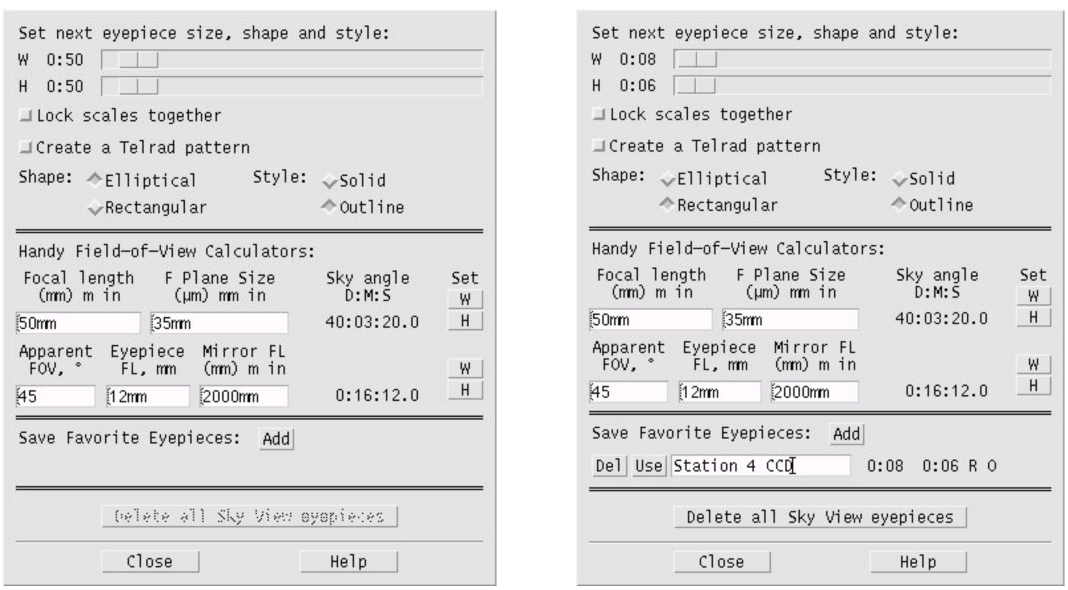
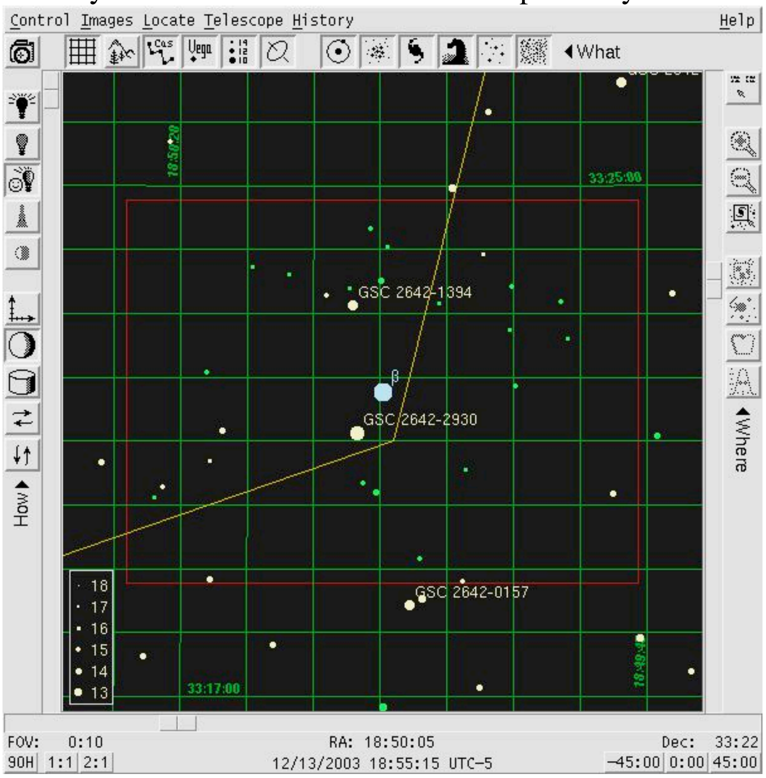


Figure 12. Sample of *XEphem* screen for defining FOV overlays to place on the sky view screen centered on your object of interest. See text for how to modify these parameters.

The sliders at the top define the width and height of the eyepiece, in degrees:arcminutes. You can set the shape to either elliptical (circular if the width equals the height) or rectangular. Once you define an eyepiece, click the "`add`" button near the bottom to add the eyepiece. It will appear below the add button, where you can name it, as demonstrated above in the right panel.

The "`Del`" button to the left of the eyepiece will delete an eyepiece. The "`Use`" button selects the eyepiece that *XEphem* will use when any eyepiece-related action is performed in the sky view. Click the "`Use`" button to select the eyepiece you've created. In the sky view, center your object of interest, then right click on it and select "`Place eyepiece`" to draw the current eyepiece. You may have to zoom in or out to see the eyepiece. Figure 13 shows a sky view of Beta Lyrae with the CCD for the telescope in bay 4 overlaid in red:



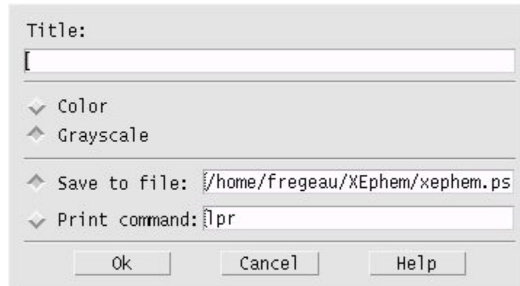


Figure 13. Sample of *XEphem* sky view with FOV overlay (left) and sample of print screen (right). See text for how to generate these windows.

Note that the orientation is RA-DEC, and not ALT-AZ. The broken yellow line through the image is simply a constellation connector, and can be turned off by clicking on the button near the top with the dots connected by lines. As mentioned before, you might want to print finder charts with all four possible mirror orientations, to ensure you get the right orientation for your telescope and CCD. Use combinations of the two buttons on the lower left, the left-right and up-down arrows, to get all possible orientations. After you observe once, you will learn which orientation to use for the finder, eyepiece, and CCD, and will only need to print the appropriate one. It never hurts to print more charts than you really need.

To print, in the sky view, go to "`Control -> Print...`", and you will obtain the print dialog: You can either print directly to the printer, or print to a postscript file. You can also add a title to your printout. The sample finder chart printout for Beta Lyrae is found in Figure 14.

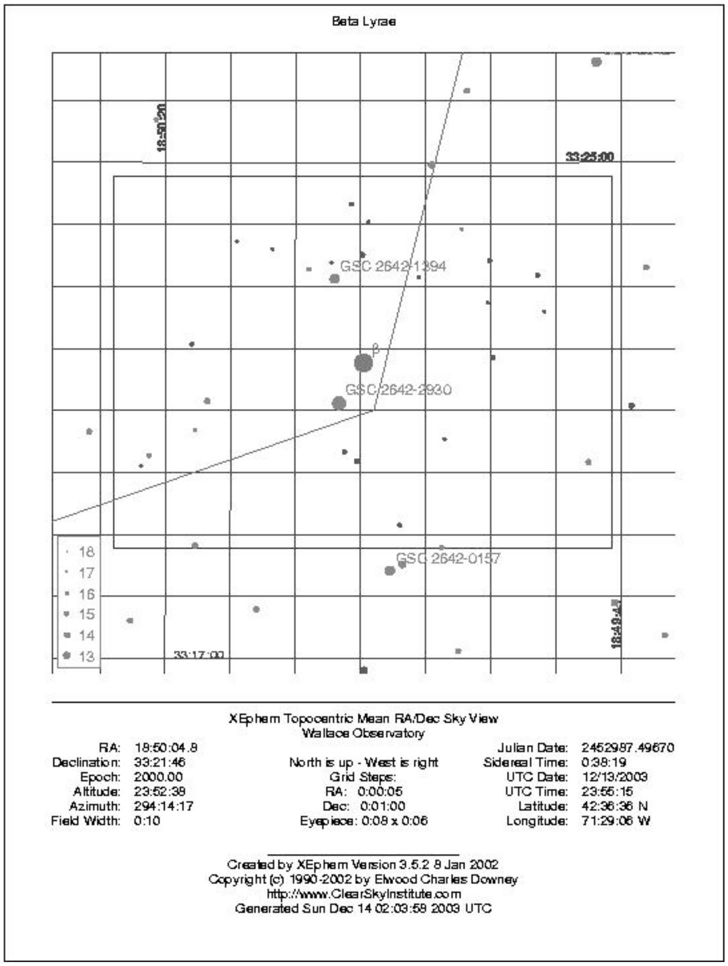


Figure 14. Sample of printed chart exported from *XEphem*.

Information relevant to your observations is printed at the bottom of the page, including the orientation of the view (which direction is North and which is West), the scale, and the observing date and time.

1.2.8 Conclusions

This tutorial only scratches the surface of *XEphem*. It has an impressively wide range of useful capabilities that the teaching staff encourages you to explore on your own.

1.3 VizieR Online Service

As mentioned before, *VizieR* can be accessed from any computer with an Internet connection. In addition to making finder charts, *VizieR* can also be used to find positions of targets and comparison stars after you have taken your images, provided you have the names of those stars. All it requires is the approximate celestial position of your object of interest.

1.3.1 How to Make Finder Charts Using *VizieR*

Instructions on How to Make a Finder Chart (before observing)

1. Follow this link to the *VizieR* website: http://vizier.u-strasbg.fr/viz-bin/VizieR

2. Input the RA and Dec under “Target Name” in the format “hours minutes seconds degrees arcminutes arcseconds”. For instance you would input “18 36 56.3 38 47 01” in order to make a finder chart of Vega. If you don’t know the exact coordinates, put in an estimate (although keep in mind that this will make the search more difficult).

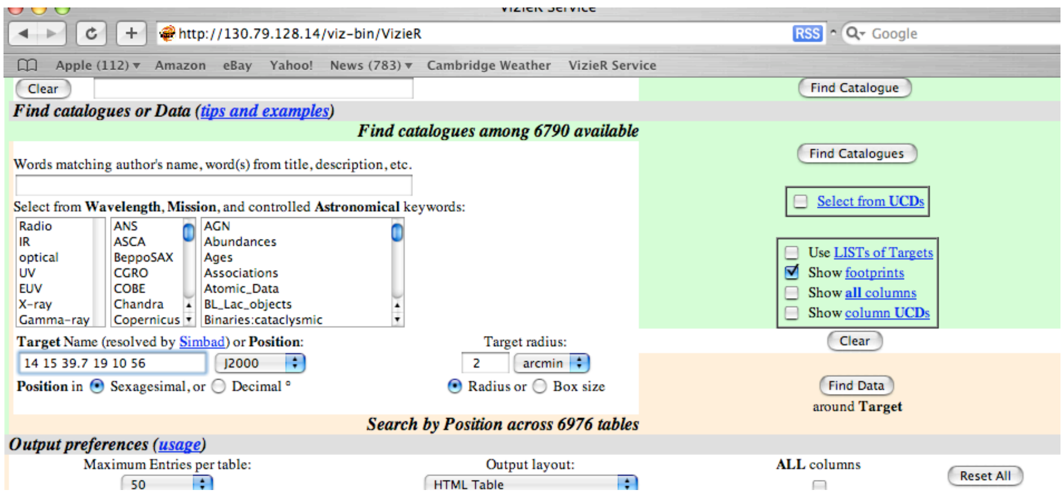
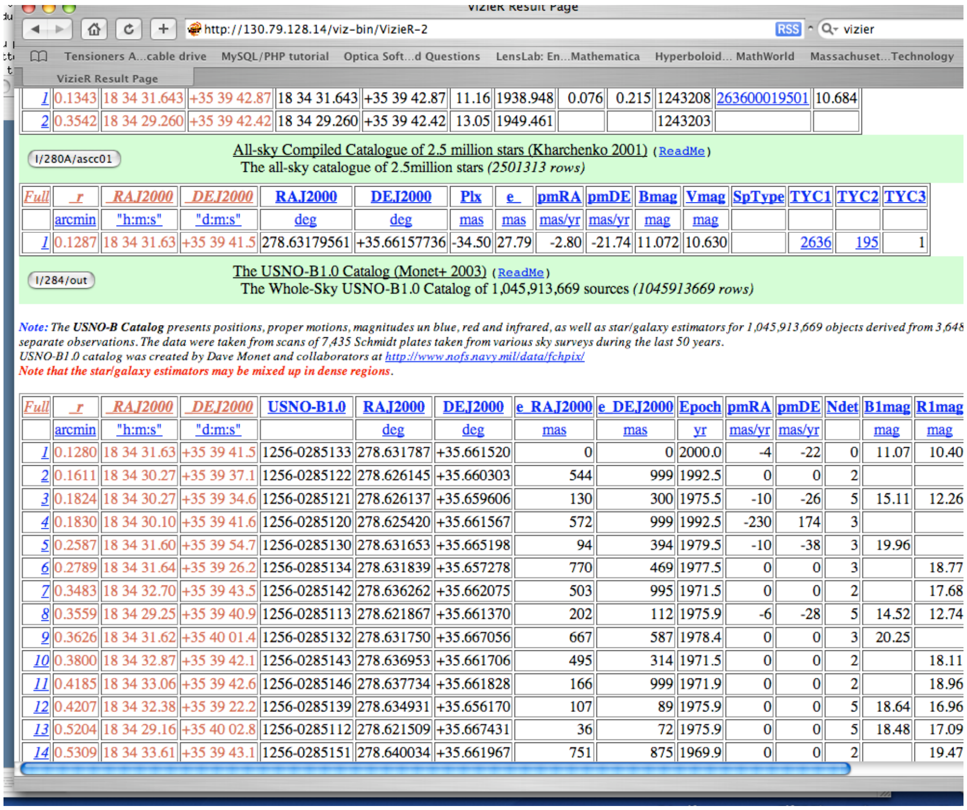


Figure 15. Sample Vizier search for Arcturus

3. Change the “target radius” according to the dimensions of your field of view.
4. Choose your “Output layout” (the standard is HTML Table).
5. Keep all other settings the same, and hit “Find Data”
6. *VizieR* searches through a number of catalogs, and will display all catalogs that contain objects within a certain radius of your input coordinates. It is possible that many of these catalogs will have your target of interest (since a single object may have multiple names, and therefore belong to multiple catalogs). Look under the 2nd column “r” which shows the distance from the coordinates you input to an object in that catalog. Scroll through the entire page to find the target closest to your coordinates. The USNO and UCAC2 lists are generally god to use.
7. Once you have chosen an object, click on the corresponding link in “Full” (1st) column. This link will lead to a Details page, which will give all sorts of information on the specific target, including name and coordinates.
8. Click the “Aladin Image” link at the top of the page, and a detailed star field will load. This may take a few minutes.
9. On the image, the target will be centered and marked with a + sign. You may click on it to get the magnitude and position to make sure it’s the right object. You will also be able to click on and get information about all other objects in that catalog in the same star field.
10. To toggle the red dots on and off, click the eye in the upper right corner.
11. To get similar fields in different sizes, go to File-> Load Astronomical Image-> Aladin Image Server. Click “Submit” and select one of the images from the list. You can also search for different RA/DEC coordinates from this window.



VizieR Result Page

1	0.1343	18 34 31.643	+35 39 42.87	18 34 31.643	+35 39 42.87	11.16	1938.948	0.076	0.215	1243208	263600019501	10.684
2	0.3542	18 34 29.260	+35 39 42.42	18 34 29.260	+35 39 42.42	13.05	1949.461			1243203		

I/280A/ascc01 — All-sky Compiled Catalogue of 2.5 million stars (Kharchenko 2001) (ReadMe)
The all-sky catalogue of 2.5million stars *(2501313 rows)*

Full	_r	_RAJ2000	_DEJ2000	RAJ2000	DEJ2000	Plx	e_	pmRA	pmDE	Bmag	Vmag	SpType	TYC1	TYC2	TYC3
	arcmin	"h:m:s"	"d:m:s"	deg	deg	mas	mas	mas/yr	mas/yr	mag	mag				
1	0.1287	18 34 31.63	+35 39 41.5	278.63179561	+35.66157736	-34.50	27.79	-2.80	-21.74	11.072	10.630		2636	195	1

I/284/out — The USNO-B1.0 Catalog (Monet+ 2003) (ReadMe)
The Whole-Sky USNO-B1.0 Catalog of 1,045,913,669 sources *(1045913669 rows)*

*Note: The **USNO-B Catalog** presents positions, proper motions, magnitudes un blue, red and infrared, as well as star/galaxy estimators for 1,045,913,669 objects derived from 3,648 separate observations. The data were taken from scans of 7,435 Schmidt plates taken from various sky surveys during the last 50 years.*
USNO-B1.0 catalog was created by Dave Monet and collaborators at http://www.nofs.navy.mil/data/fchpix/
Note that the star/galaxy estimators may be mixed up in dense regions.

Full	_r	_RAJ2000	_DEJ2000	USNO-B1.0	RAJ2000	DEJ2000	e_RAJ2000	e_DEJ2000	Epoch	pmRA	pmDE	Ndet	B1mag	R1mag
	arcmin	"h:m:s"	"d:m:s"		deg	deg	mas	mas	yr	mas/yr	mas/yr		mag	mag
1	0.1280	18 34 31.63	+35 39 41.5	1256-0285133	278.631787	+35.661520	0	0	2000.0	-4	-22	0	11.07	10.40
2	0.1611	18 34 30.27	+35 39 37.1	1256-0285122	278.626145	+35.660303	544	999	1992.5	0	0	2		
3	0.1824	18 34 30.27	+35 39 34.6	1256-0285121	278.626137	+35.659606	130	300	1975.5	-10	-26	5	15.11	12.26
4	0.1830	18 34 30.10	+35 39 41.6	1256-0285120	278.625420	+35.661567	572	999	1992.5	-230	174	3		
5	0.2587	18 34 31.60	+35 39 54.7	1256-0285130	278.631653	+35.665198	94	394	1979.5	-10	-38	3	19.96	
6	0.2789	18 34 31.64	+35 39 26.2	1256-0285134	278.631839	+35.657278	770	469	1977.5	0	0	3		18.77
7	0.3483	18 34 32.70	+35 39 43.5	1256-0285142	278.636262	+35.662075	503	995	1971.5	0	0	2		17.68
8	0.3559	18 34 29.25	+35 39 40.9	1256-0285113	278.621867	+35.661370	202	112	1975.9	-6	-28	5	14.52	12.74
9	0.3626	18 34 31.62	+35 40 01.4	1256-0285132	278.631750	+35.667056	667	587	1978.4	0	0	3	20.25	
10	0.3800	18 34 32.87	+35 39 42.1	1256-0285143	278.636953	+35.661706	495	314	1971.5	0	0	2		18.11
11	0.4185	18 34 33.06	+35 39 42.6	1256-0285146	278.637734	+35.661828	166	999	1971.9	0	0	2		18.96
12	0.4207	18 34 32.38	+35 39 22.2	1256-0285139	278.634931	+35.656170	107	89	1975.9	0	0	5	18.64	16.96
13	0.5204	18 34 29.16	+35 40 02.8	1256-0285112	278.621509	+35.667431	36	72	1975.9	0	0	5	18.48	17.09
14	0.5309	18 34 33.61	+35 39 43.1	1256-0285151	278.640034	+35.661967	751	875	1969.9	0	0	2		19.47

Figure 16. Vizier search results page. Click on the left column marked "full" to get more information about that star.

12. Print this image to use as a detailed finder chart to supplement your simpler ones. Go to File-> Save the Current View-> JPEG

1.3.2 How to Use *VizieR* to find Positions of Comparison Stars (for Astrometry)

Suppose you are back in the lab and have an exposure that corresponds to the finder chart you made using Starry Night. Your exposure consists of your target and a few comparison stars. Since Starry Night only gives approximate positions, you would like to know the most exact positions of your comparison stars in order to have reference values for your astrometry calculations.

Instructions on How to Find Positions of Stars (after observing)

1. Find the names or ID numbers of the comparison stars of interest using *Starry Night* and the approximate relative distances of your comparison stars to the target.
2. Follow steps 1-5 of Sect. 1.3.1 - How to Make Finder Charts Using VizieR for your target.
3. A number of catalogs will come up. Using the names of your comparison stars along with the relative distances to your target, decide which stars listed are those that you are looking for.
4. Follow steps 7-9 of Sect. 1.3.1 - How to Make Finder Charts Using VizieR in order to find the comparison star positions.

2 Finding an Object with the Telescopes at Wallace Observatory

In this section we discuss how to use the telescopes at the George R. Wallace, Jr. Astrophysical Observatory to find objects in the sky, and to center them in the eyepiece of the instrument. This process is essential, of course, prior to making any astronomical measurement.

The telescopes available to you are permanently mounted in the "shed" and include:

One 14-inch telescope with a spectrograph (bay 1)
One 11-inch telescope with a CCD camera (bay 2)
Two 14-inch telescopes with CCD cameras and automated mounts (bays 3 & 4).
(These can be used at Wallace, or occasionally remotely from the astronomy lab in 37-292. See class announcements for remote observing opportunities.)
One 16-inch telescope with a CCD camera in the smaller of the two domes.
Additional 8-inch telescopes with CCD cameras that can be set up in driveway if needed

More information about these telescopes and instruments can be found at the URL
`http://web.mit.edu/wallace/`

2.1 Operating the Wallace Shed Telescopes

All the telescopes in the shed are set up in what is called "Polar alignment". This means that the axis of the telescope is along the same line as the Earth's rotation axis, which is within one degree of the north star, Polaris. The telescopes pivot around this axis and have a motor that tracks the sky's motion in the east-west direction so that once you point at an object it does not run out of the field. When you start the night you will need to do the following:

1. Take all the lens covers off of the telescope.
2. Turn the power strip on the telescope pier to "on".

Push the power button on the computer (little button on the top right of the back of the Mac Mini computers) and let it boot. You should see a number of lights at this point: the power lights from each of the power strips (one on the pier, and one on the desk), as well as the USB hub light. You should also hear the fan on the CCD camera. If any of these fails to light, or you do not hear the fan turn on there may be power/connection problems, and you should discuss this with your TA.

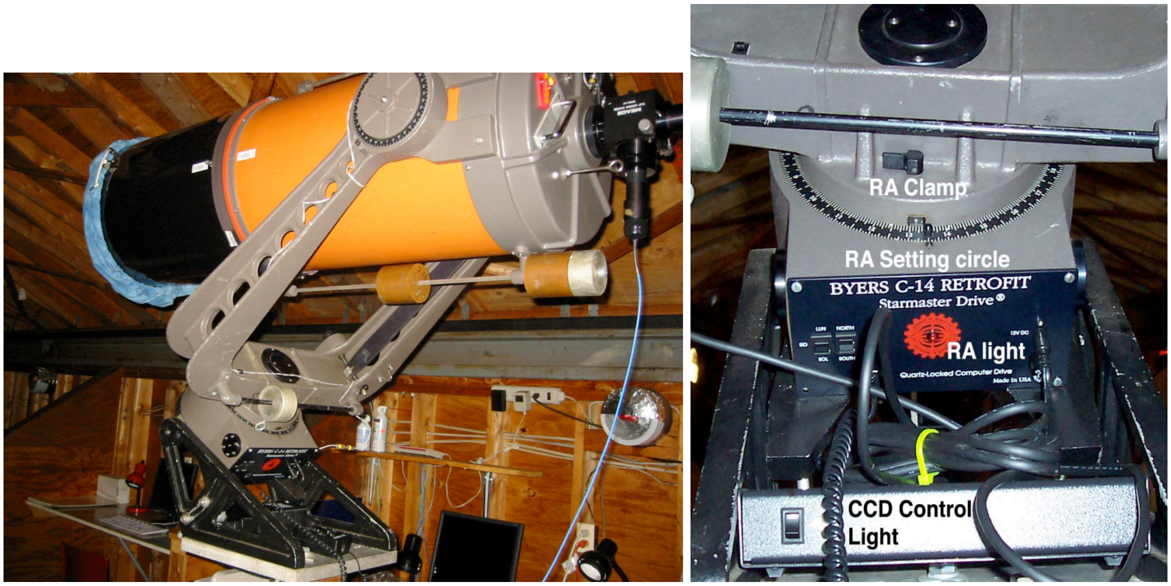


Figure 17. 14-inch Celestron telescope set-up, the tube is to the left and the base is to the right. Knobs, clamps and other things of interest are labeled.

2.1.1 The 14-inch Celestron manual telescope in Bay 1

Figure 17 pictures the base and side of the 14-inch Celestron. To move the telescope in "Declination" (DEC) or the North-South direction, you need to loosen the clamp on the upper right-hand side of the telescope (left picture above). Be sure when you move the telescope you only grab onto it by holding the hand catches and the fork of the telescope. **NEVER grab the camera extension or the finder scope; this will be disastrous.** Tighten the clamp when you have moved to your desired location. To move the telescope in "Right Ascension" (RA) or the East-West direction, you need to loosen the clamps at the circular base of the telescope (right picture above). There are two clamps — one on each side of the base — you need to loosen both. Again move the telescope to the desired location and tighten both clamps. At times you will want to loosen both directions (DEC and RA) simultaneously and use the finder scope to locate the patch of sky you are interested in finding. Once you get close to your object you can lock up the telescope and use the hand paddle to search for and center your object with the fine adjustment paddle motion than is feasible with the clamps free.

You will need several eyepieces for finding your field and recording data.

1. Use the Telrad and/or setting circles to point the telescope in the general direction of the target (Figure 18)

Figure 19. 14-inch Celestron telescope with Telrad (right), and with 40mm Plossl eyepiece (left)

2. Use the 40mm Plossl eyepiece to locate the starfield and position the target near the center of the field of view (Figure 18). Use the "F" speed on the Byers drive handpaddle.
3. Use the reticle eyepiece to precisely center the target in the FOV. Use the "G" speed on the handpaddle to position the object in the crosshair "box." Note: you will have to refocus slightly vs. the 40mm, but do not refocus once the reticle eyepiece is focused. The fiber optic "eyepiece" is parfocal with the reticle eyepiece so no further focusing is required

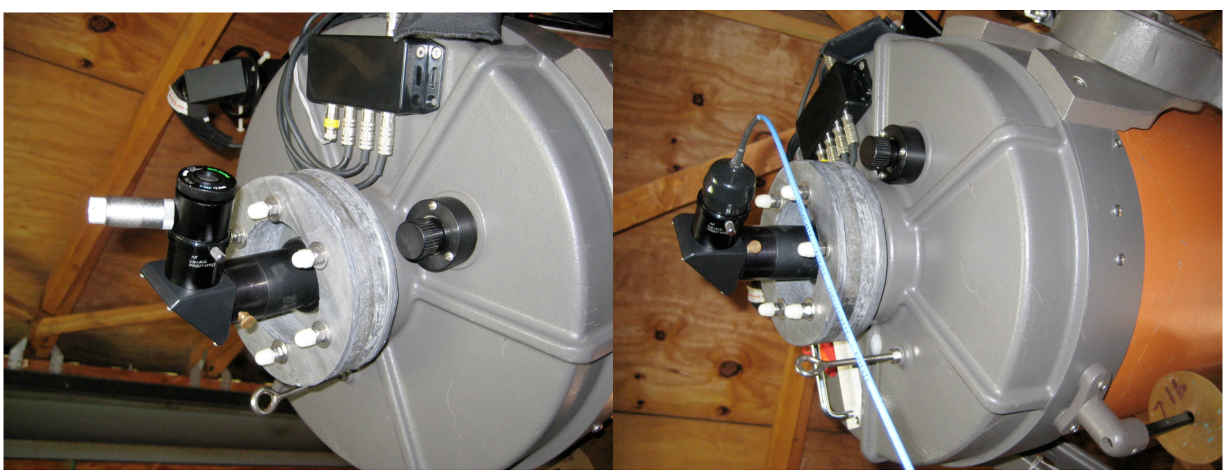


Figure 19. Reticle eyepiece (left) and fiber optic eyepiece assembly (right).

4. Once the target is centered, exchange the reticle eyepiece with the fiber optic eyepiece assembly. If there is insufficient slack in the fiber, you will have to rotate the diagonal (as shown in the figure) to a more "sideways" position – the fiber optic requires a minimum 3" radius of curvature to function properly. Once the diagonal is rotated you will have to reinsert the reticle eyepiece and re-center

the target before inserting the fiber optic eyepiece. You can save yourself this double swap if you anticipate a fiber limit and pre-rotate the diagonal in Step 3 above.

5. With the fiber in place, record your data with CCDSoft as described in Section 3.1.
6. Repeat steps 1 through 4 for each target.

Shutting down Pier 1:

1. Re-insert the 40mm (with cover) in the diagonal. Place the capped fiber optic eyepiece (on its side) on the top of the concrete pier to the right of the power strip. Check power OFF on the reticle eyepiece and store it and the Byers handpaddle on the metal shelf next to the camera and telescope drive power supplies.
2. Return the telescope to its stow position (the position it was in when you started the night) and return all of its covers.
3. Port your data to titania
4. Turn off the power strip on the pier.

Note: Always leave the eyepiece diagonal mounted on the telescope. If the telescope is pointed to a low sky position, the diagonal may be rotated so as to facilitate viewing, however, do not move/rotate the diagonal (or refocus the telescope) once the reticle eyepiece has been lined up on a given target. Rotating the diagonal causes a slight image shift that may move the target off of the fiber tip.

2.1.2 Telescope in Bay 2

This telescope is smaller than the other telescopes in the shed. You NEVER want to loosen the clamps on this telescope, as it will lose knowledge of the direction in which it is pointing. To move this telescope in any direction you MUST use the hand paddle (Figure 20).

1. Turn everything "on" as you would with any of the other shed scopes. Lastly "boot up" the telescope by pressing the power switch on the back of the telescope base on the left side. Now look at the hand controller.
2. The controller screen will display: "`Wake Up`"
3. Press `ENTER` to wake from Hibernate, `UNDO` to exit.
4. Press `ENTER`.
5. The controller will display the current time, location, and other information. Scroll through this using the `UP` and `DOWN` keys (6 and 9 on the controller keypad) and make sure this information is correct. If so, press `ENTER`. If not, press `UNDO` and edit the information.
6. Once you have accepted the information, sidereal tracking will turn on. Press the `UNDO` button until you reach the top-level menu, the hand controller will

display “NexStar GPS”. You can now begin using the goto features of the telescope, move the telescope by hand with the four arrow keys, or move to objects using *TheSky6™* .

7. Open *TheSky6™* , and link to the telescope using the green telescope icon. Unlike the telescopes on piers 3 and 4, you do not need to home or park the telescope.
8. Sync the telescope using the hand controller (not *TheSky6™*).

Figure 20. 11-inch Celestron control paddle.

More detailed descriptions of how to find objects with this telescope can be found in the manual next to the computer in Bay 2.

At the end of the night you must put this telescope into Hibernation mode so that it will retain its alignment and the next person to use it wakes it up with it knowing where it is. To do this:

1. Unlink *TheSky6™* using the red telescope icon.
2. UNDO to the top-level menu.
3. Press the MENU button (3 on the keypad), and scroll down to the UTILITIES menu. Select the menu by pressing ENTER.
4. Scroll down again until you see HIBERNATE. Press ENTER. The controller will show: “Position Scope”
5. “Move the scope to a convenient position, press ENTER when ready”.
6. Use the direction buttons to move the telescope to the home position (tube pointing south and parallel to the floor). You may need to change the rate in order to move the scope in a reasonable time frame. When the scope is in position, press ENTER.
7. The controller will now show: “POWER OFF”
8. “Turn power off when ready, do not move scope. UNDO to exit.”
9. Power down the telescope by turning off the rocker switch located on the left rear of the telescope base.

Other Notes:

- The four directional buttons are for moving the telescope only, they will not scroll through a menu. To scroll, use the `UP` and `DOWN` keys (6 and 9 on the keypad).
- Pay attention when moving the scope with a "`GOTO`" command. There are slew limits set so that neither the camera nor the tube will run into the base of the telescope. When a limit will be breached by a `GOTO` slew, the hand controller will display a slew limit warning and ask you whether to continue or cancel. If you are sure the telescope can point where you want to go, have a lab instructor check your coordinates. ONLY a lab instructor SHOULD OVERRIDE A SLEW LIMIT WARNING!!
- In the event that you need to cancel a `GOTO` move while the scope is still moving, press one of the direction buttons. The `UNDO` button will NOT stop the slew. Canceling a move in this way does not seem to affect the alignment.
- In order to change the driving speed, you need to use the `RATE` button. Rates go from 1 to 9 with 9 being the fastest. In general, 3 (4x sidereal rate) is a good speed for eyepiece viewing, 7 (.5°/sec) for the finder, and 9 (3°/sec) for slewing. To change the rate, press the `RATE` button followed by the number of your desired speed. The number will show up briefly on the upper right of the hand controller screen.
- A `GOTO` move usually takes about 10 seconds to center up after the fast slewing. A bar will rotate in the upper right corner of the hand controller screen until the scope has stopped moving. Do not try to move the scope until this bar has disappeared.
- Most commands need to be initiated from the top-level menu. To get there, press `UNDO` as many times as necessary until the hand controller screen displays "`NexStar GPS`".

2.1.3 Telescopes in Bays 3 & 4

These telescopes are both controlled by a Paramount ME™ mount. These were upgraded from Celestron mounts to Paramount ME™ automated mounts in Summer 2007 and were developed to enable data-taking for 12.410 from the astronomy lab (37-292). You will be using *TheSky6™* software (on the desktop in the Bay) to operate the telescope, and *CCDSoft™* (Sect. 3.1) to operate the CCD (also on the desktop). Although these telescopes are automated, you must still demonstrate your knowledge of how to operate the mount during your lab session, recover from mount errors, and verify the telescope is indeed pointing where it should be. The following instructions are imperative to ensure proper use:

Figure 21. Telescopes in piers 3 and 4

Set-Up of the Telescopes and Computer

1. Turn the computer on (may need to turn power strip on) in the bay by pressing the button on the back of the small Apple drive next to the monitor. The computer should automatically start up Windows (If, for some reason, it starts up in Mac OS, restart the computer holding down the "Option" key, and select Windows).

2. Turn on the power strip located on the pier, under the telescope mount. This will cause the mount to start humming, and it should make two separate beeps. You will know that the camera is on when you can hear its decently loud fan. The focuser will start counting up to the last position it was set at. Do not connect to the camera until the focuser has stopped counting.

3. On the computer, open up *TheSky6™*, located as a shortcut on the Desktop.

4. In order for the telescope to be correctly oriented, it must be put in Home position before every observing run. This can be done by using *TheSky6™*: go to the "Telescope" menu item, scroll down to the "Link", and select "Establish". The software will link up to the telescope, and ask you if you want to home the telescope. Select "yes". You may also home the telescope by pushing the button on top of the joystick twice, quickly, or by selecting "Find Home" under the "Telescope" and "Options" menus.

Either use the software or the joystick to home the telescope, but do not use both methods. If you get an error telling you that *TheSky6™* is not connected to the computer clock, make sure the icon telling it to do so is selected in the toolbar.

5. The telescope will begin to move into its "home" position. Make sure to keep any restricting cords out of its way. You will know when the telescope has been homed when you hear two separate sets of three beeps.

6. Now that the telescope has been homed, you can control it using *TheSky6™* software or the joystick. Use of the *TheSky6™* software is in Sect. 2.3.

Turning off the Telescope and Computer

1. Put the telescope back in the "Park" position, (In *TheSky6™*, go to "Telescope" → "Options" → " Park"). You MUST park the telescope before shutting down. This immobilizes the telescope (in case you forget to turn off the power strip, it will not keep tracking and hit the roof) and helps put it in proper alignment for your next observing run.

2. It is now safe to turn the power off. Do so on the power strip on the mount.

3. Shut down the computer.

Important Notes

- The telescope mounts have two positions: telescope on the east side with the counterweight on the west side, and telescope on the west side with the counterweight on the east side. The mount cannot track to a position where the telescope is below the counterweight. Because of this, you cannot take a series of images of an object crossing the meridian. If you do, the telescope will stop tracking, and the images of stars will look like long lines. *TheSky6™* will warn you of this by displaying your object going into a pink "danger zone." This is a buffer of about 10 minutes on either side of the transit time (when the object will pass over the meridian). You can look up the transit time beforehand in *TheSky6™* . Once your object has passed into the "danger zone," you can re-slew to the object (the telescope mount should turn all the way around) and continue taking images.
- If you notice that the telescope pointing is off, do not attempt to sync it. A class instructor can show you how to fix this without deleting the pointing model the mounts build up.

2.2 *Operating the Wallace 16" Telescope*

The 16" telescope is located in the dome to the east of the shed. Its mount has recently been rebuilt, and will now work with *TheSky6™* (Sect. 2.3) for finding and tracking targets, and *CCDSoft™* (Sect. 3.1) for taking images.

Figure 22. 16-inch Telescope. The finderscope and guidescope are located above the main telescope.

Setup

1. Open dome shutter by releasing rubber latch, and cranking opener.

Figure 23. Dome shutter. Open by releasing the rubber latch in the center, and cranking the handle on the right.

2. Remove cover from telescope.
3. Remove covers from finderscope and guidescope (if needed) – it may be easier to remove these covers later with the telescope pointed more towards zenith.
4. Turn on the power bar on the right side of the desk.

5. Turn on the Mac cube with the switch on back (under desk towards right.)
6. Turn on the TCS PC (under cube.)
7. Update the PC clock, if necessary, to the current UTC by right clicking on time in the lower right hand corner of screen and selecting "Adjust Date/Time." Leave the time zone at (GMT) Casablanca and set current UTC under time window (EDT+4, EST+5), verify the date is "tomorrow" if UTC is after midnight (>12 am). Be sure to verify that the AM/PM option is correct.
8. Start the *TCS* program by clicking the *TCS* icon. This is a DOS program with runtime menus along the bottom of the screen.
9. Enable the serial port for *TheSky6™* interface by using the arrow keys to select the "pArameters" submenu.
   - Press ENTER, then press ENTER again to select "Input"
   - Select "Remote"
   - Use the down arrow key to highlight "COM4" (which should already be designated by ">>")
   - Press ENTER twice, the ">>" will cycle off, then on (it will also cycle the grey "*TheSky6™*" label- towards the lower right of the screen. This is a sign that it is connected to *TheSky6™* .)
   - Press ECS three times to back out.
10. Turn on the power bar at the base of the RA axis (towards dome slit)
    - This will power telescope controller (black box below RA drive), which, in turn, powers the stepper drive motors and the STL1001 camera
    - Caution: this power strip should never be on without TCS running.
11. Login to the Mac
12. Start *TheSky6™* and *CCDSoft™* .
13. In *TheSky6™* , click the "Establish Link" green telescope icon. You will know that it is connected when "TheSky" starts to flash on and off in the TCS program. You can now turn off the TCS monitor to reduce unnecessary light.
14. Set up *CCDSoft™* as explained in Sect. 3.1.

Dome Controls

1. Slew the telescope to the first target, or a nearby reference star using *TheSky6™* (you do not need to "home" the telescope first, unlike the setup in shed telescopes 3 and 4). Note the altitude and azimuth values of the target from the object dialog box.

Note: The telescope controller has three power settings: Variable, Slew, and Track. The controller will normally be left in Variable, which should provide enough power for slewing. If either stepper motor stalls (high pitched whine from either motor), use the F9 key (labeled Stop) to cancel the current move command, which will result in the drive losing its position info. The telescope will then have to be resynched (see below) on a celestial target. If the motor(s) continue to stall, get help.

2. Use the alt/az values to determine the initial dome slit position.

3. Using the reference table to the left of the Mac keyboard, look up the dome position index value (0-40.9) associated with the target alt/az coordinates.
4. Use the dome rotation buttons to move the dome position value (from the reference table) over the index (blue arrow/pointer.) The dome motor control buttons are located on the southwest corner of the pier near the red LED (the red LED is on the dimmer that controls the brightness of the dome position light.) The rotation controls consist of three buttons, the outer two start rotation of the dome in the selected direction, while the middle (red) button stops rotation (and must be used before reversing direction.)

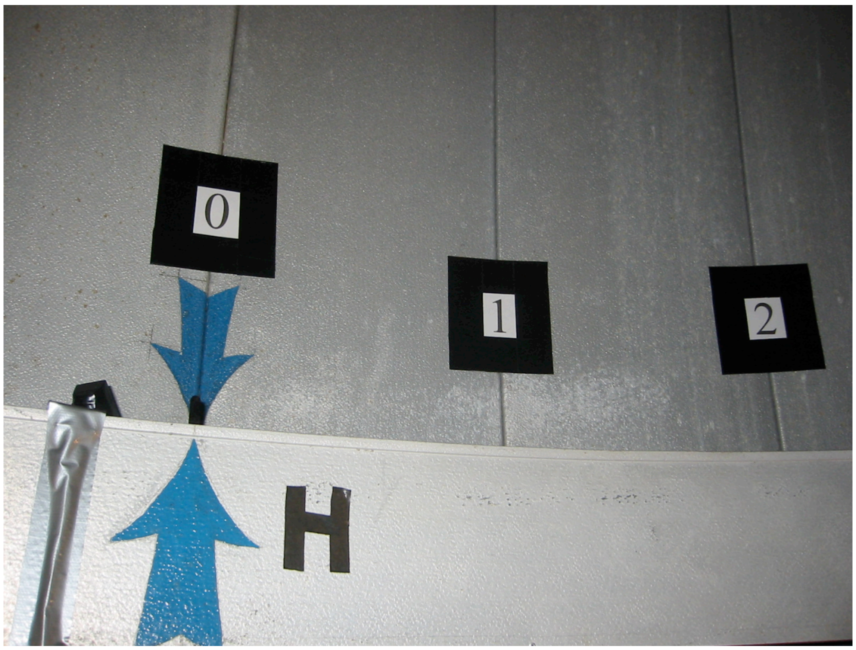


Figure 24. Dome rotation markers. For the correct dome position, line up the bottom arrow with the number given by the chart next to the computers.

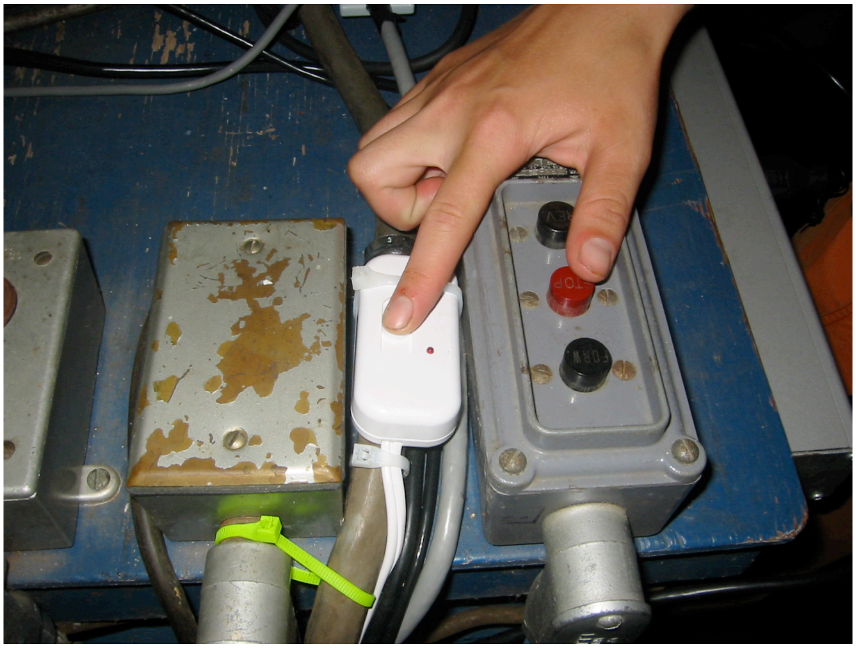


Figure 25. Dome rotation controls. The white slider will turn on a light that illuminates the dome numbers. The black buttons on the grey controller move the dome, and the red button stops the rotation.

5. The initial dome position will be good for 10 minutes or so, but will have to be updated regularly since the dome does not autotrack.
6. Once you have set the dome position, take an image with *CCDSoft™* to check the pointing and focus. You will rarely need to adjust the focus, but will almost always need to adjust the pointing. Follow the steps in the two sections below to fix these issues.

Focusing

1. Under the *CCDSoft™* Focus Tools tab, activate continuous focusing exposures. (max. 1sec) Click on "Take Image" with the "Continuous" box checked.
2. Check to see how the focus of the images looks. Refocusing is rarely required on this telescope.
3. If focusing is necessary, turn the power on for the Blue DAEDAL controller under the desk. This provides power to the old hand controller with small focus pushbuttons near white guard at top (note- all other buttons/switches on this paddle are disabled)

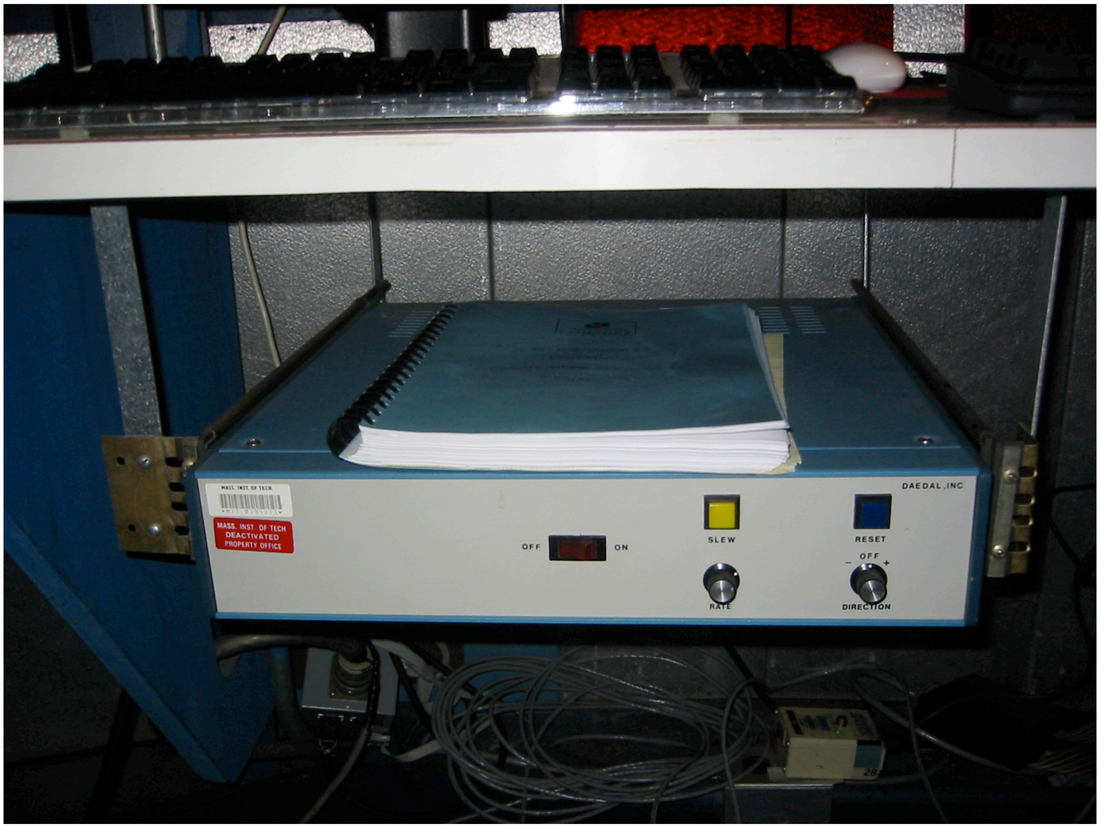


Figure 26. DAEDAL controller. This only needs to be turned on during focusing.

4. The pushbuttons move the focuser at one rate, so very short "pulse" inputs will be required to achieve sharp focus.

Figure 27. Focus controller. The two buttons to the left in this picture will move the focuser.

5. Once focusing is complete, you can power down the DAEDAL if desired to eliminate the cooling fan noise (you'll have to turn it back on whenever re-focusing is required, which should not be too often.)

Syncing Telescope

1. Once focusing is complete, use the pushbuttons on the larger black TCS handpaddle to center the target in the FOV. In *CCDSoft™* , you can zoom out to see the whole image in one screen, and see where the center is by selecting "Image" -> "Show Cross Hair" note: the center cursor "box" is 30 arcsec wide on the STL 1001.
2. Use the GUIDE and DRIFT pushbuttons on the hand controller for small (DRIFT) and very small (GUIDE) corrections. When centering on the cursor box, the GUIDE rate should be adequate.
3. Once the object is centered, click on the object in *TheSky6™* , go to the "Telescope" tab of the object dialog box, and click "Sync." This will synchronize TCS and *TheSky6™* .
4. You should repeat step 3 every time you move the telescope with the handpaddle. You should resync the telescope as often as necessary.

Figure 28. TCS handpaddle. Use the directional buttons to move the telescope, and the Guide/Drift/Slew buttons to adjust the rate.

Exiting

1. Unlink *TheSky6™* and TCS (red telescope icon)
2. Disconnect camera (*CCDSoft™* "Camera" -> "Setup" ->"Disconnect")
3. Turn off DAEDAL focuser power, if on
4. In TCS, highlight "shutDown." Press enter twice, and the telescope will slew to park position.
5. Turn off power bar at base of RA axis: this will shut down the telescope controller and camera.

6. Press enter one more time in TCS to exit program.
7. Quit *TheSky6™* and *CCDSoft™* . Do not save any changes.
8. Transfer data
9. Shutdown TCS PC and Mac Cube, then power bar at the right edge of the desk.
10. Replace cover on telescope and finders.
11. Rotate dome to park position (blue arrows/"0" index)
12. Close shutter.
13. Turn off all lights and lock doors.

2.3 Using TheSky6™ Software for Telescopes 3 & 4

TheSky6™ is a software only compatible with Windows, and is therefore only on the Macs that run Windows (the desktops located in Bays 3 & 4). It is used to control the movement of the automated telescopes, and is very simple to use. The following are some basic commands, but feel free to experiment with the program yourself.

1. Open *TheSky6™* via the shortcut located on the desktop of the computer.
2. Follow the instructions in Sect. 2.1.3 in order to home the telescope if you are using one of the telescopes in pier 3 or 4.
3. Right-click on the star chart, which creates the background of *TheSky6™* . Go to "Find" and type in your object of interest.
4. To access the database of extended minor planets, go to "Data," "Extended Minor Planets," make sure the astorb file is selected, and click "Compute."
5. If your object is in the database of *TheSky6™* , a window will pop up with information about your object (such as current altitude, rising and setting times, coordinates). Before moving the telescope to that object, make sure that the altitude is above 20 degrees.
6. Click on the rightmost button at the bottom of the window, "Slew". The program will then verify that you want to slew to that object.
7. The telescope will start to move. Be careful to keep yourself and other cords out of the way. The automated mount may take a strange path to get to its destination, but do not interfere with the telescope while it is moving.
8. Your object of interest should be in the camera FOV, but you will need to center it via the joystick. You can take exposures in *CCDSoft™* following instructions in Sect. 3.1.
9. In *TheSky6™* , you may also input celestial coordinates if your specific object is not in the database. Go to "Orientation," "Move To," and make sure the program is in equatorial mode.
10. Be sure to Park the telescope by the instructions in Sect. 2.1.3 – Telescopes in Bays 3 & 4 before closing the program.

Now that you understand how to plan for observations and operate the telescopes and the computer software, you are equipped to use this instrumentation to collect real astronomical data.

2.4 *Exercise*

This exercise illustrates the relative difficulty of locating objects of different brightnesses in the sky with our telescopes. It should also to give you an idea of what types of finder charts that you will want to make for your own projects. The finder charts in Figure 29–Figure 32 are not necessarily optimal, but should give you an idea of what to strive for. Two charts are included for a few of the objects of interest, a "distant" finder chart to get yourself oriented in the sky with respect to the constellations and a "close-up" finder chart so you know what you should see in the finder, eyepiece or camera. Some of the telescopes have automatic control software, but you need to have finder charts. The telescopes will point close to your object, but they are not perfect and you need to be able to identify what you are looking at.

Choose a partner and locate the following objects in the sky with the telescope. Start by locating the object in the finder scope (center it in the finder) then look in the main eyepiece and center it with the fine controls. In your lab notebook draw a picture of what you see in the finderscope and the eyepiece (see next page). Make notes for yourself about anything that helped/hindered you in finding these objects or significant differences between the finder and eyepiece (orientation, ease of seeing an object etc.)

1. The Moon
2. Vega ($V = 0.0$), Altair ($V = 0.75$) or Deneb ($V = 1.25$)
3. M31 ($V = 4.5$)
4. Uranus ($V = 5.7$)
5. M11, the Wild Duck open cluster ($V = 7.0$)
6. M57, the Ring Nebula (V=9.7)
7. NGC 6756, Open cluster (V=~11)

Also make some notes in your book about the conditions of the evening. Is the Moon up (how full is it)? Is the Moon close to any of the objects you want to look at? Are there clouds? Does the air seem still or is it turbulent? What time is it (beginning and end of observations)? Where are you located? What telescope are you using and who is your partner? The more information you can record about the conditions on a night you are collecting data, the more information you don't have to "just remember" when you are trying to figure out your data analysis. If in doubt, write it down! Find as many of the objects listed as you can in the time allotted for this evening and record your findings in your notebook or in the sample area below.

Finderscope   Eyepiece

Object: ____________________

Date/Time: ____________________

Filter: ____________________

Comments: ____________________

Weather: ____________________

Finderscope Eyepiece

Object: ____

Date/Time: ____

Filter: ____

Comments: ____

Weather: ____

Finderscope Eyepiece

Object: ____

Date/Time: ____

Filter: ____

Comments: ____

Weather: ____

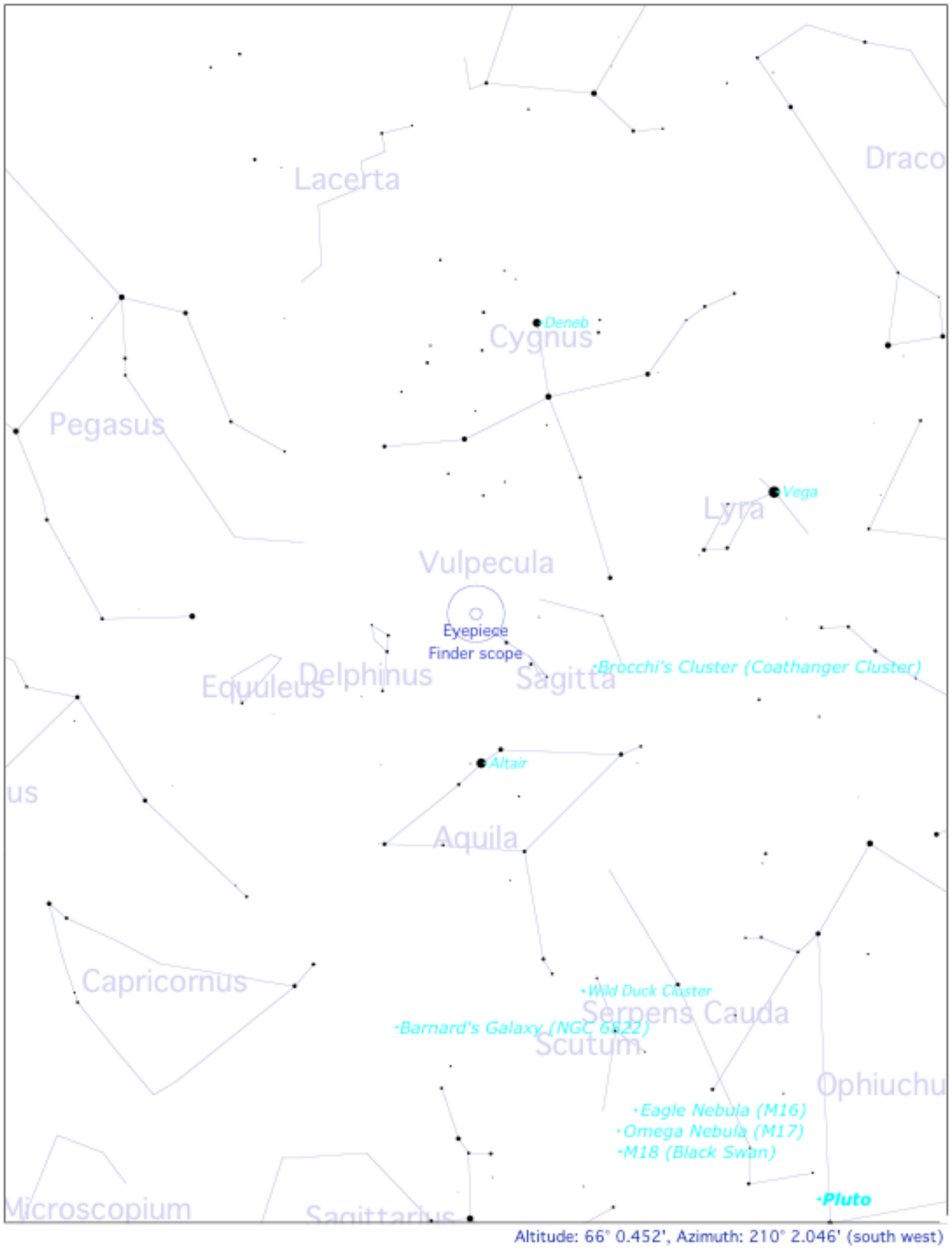


Figure 29. Sample finder chart for locating bright stars in the Summer Triangle: Vega, Deneb and Altair. North is up, and East is to the left. This is a standard view, and all of the finder charts here follow this convention. This finder chart has a large field of view, and while Pluto will be below the horizon in early fall, the rest of this chart will extend to where you can easily see it.

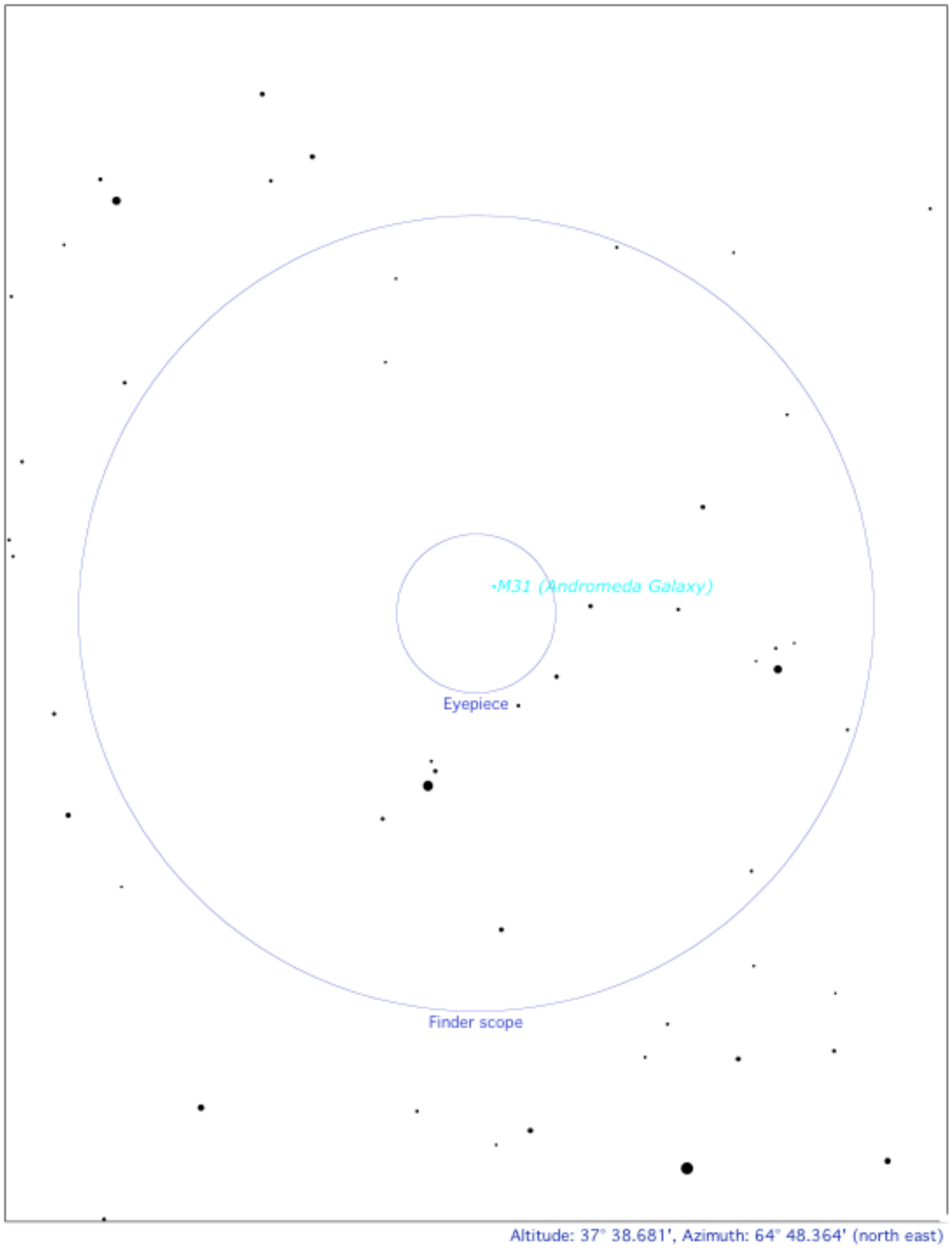


Figure 30. Sample finder chart for locating M31 (The Andromeda Galaxy) with field of view overlays for the finderscope, and the eyepiece.

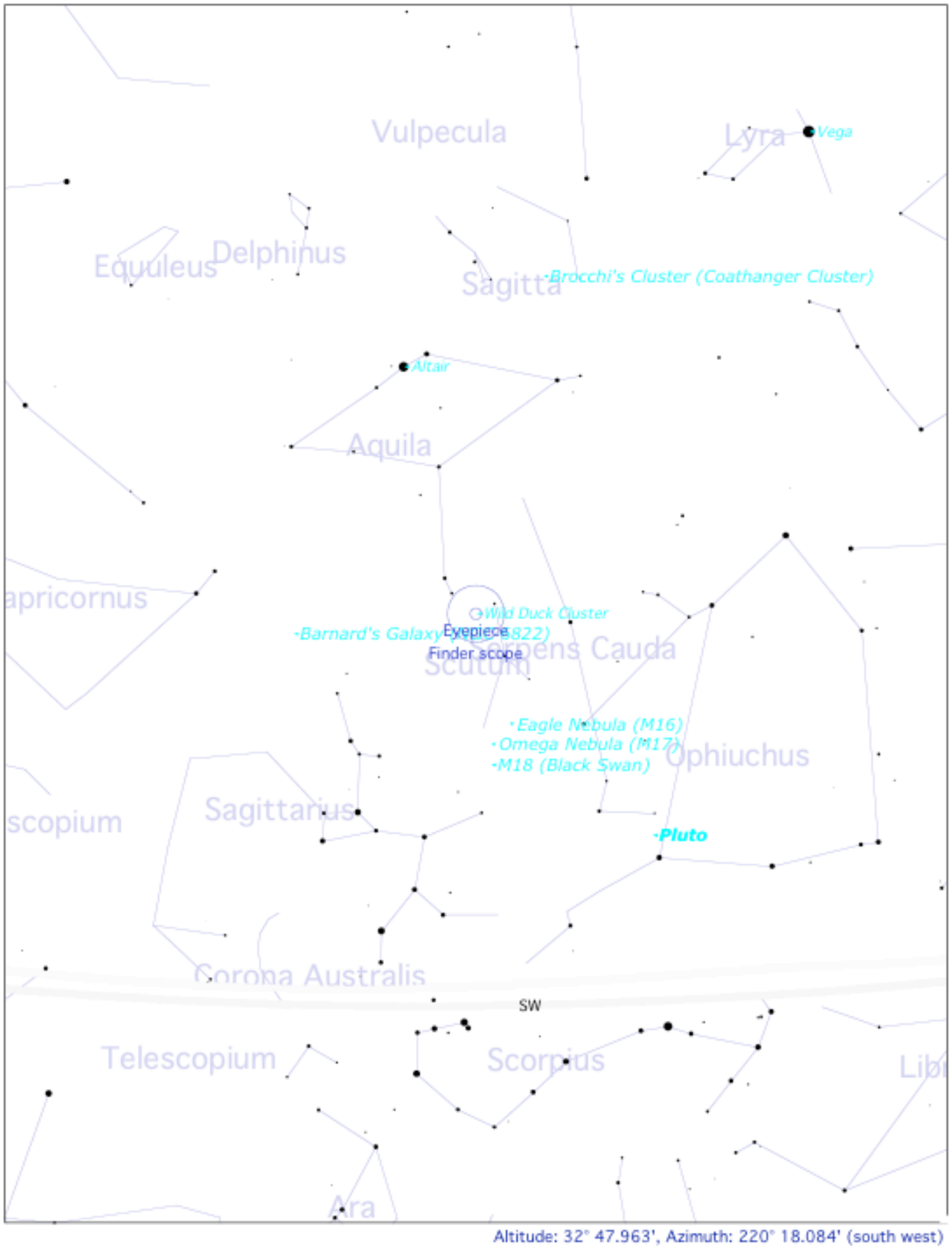


Figure 31. Sample wide-field finder Chart for the M11 (The Wild Duck Cluster). This finder chart shows M11 scaled for you to see its position relative to several constellations that you can see with your naked eye. It does not give sufficient detail to center M11 in the CCD camera on any of the telescopes.

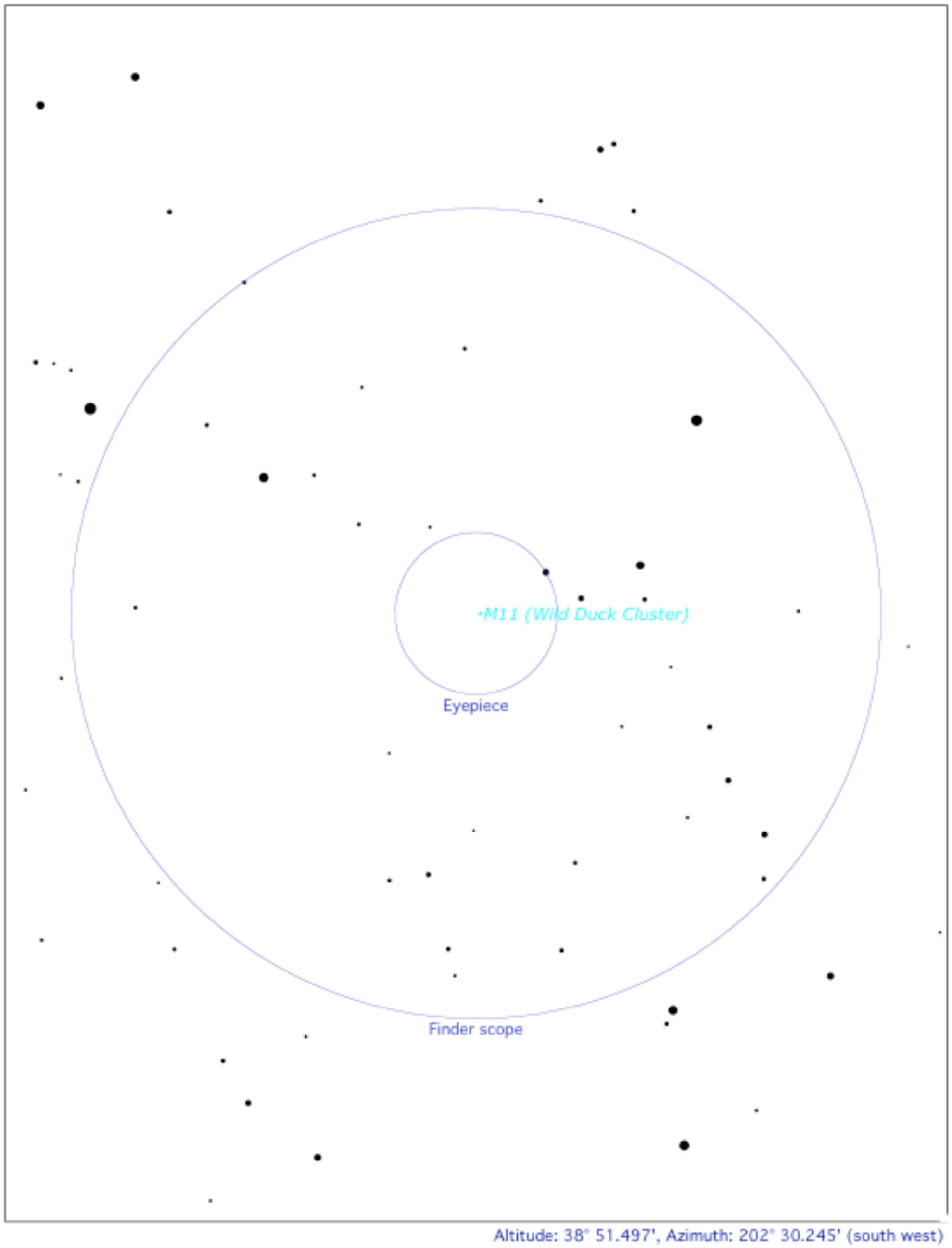


Figure 32. Sample narrow-field finder Chart for the M11 (The Wild Duck Cluster). This finder chart shows M11 scaled for you to see its position in the finder telescope (mounted on the side of each large telescope) and for you to see its position within the eyepiece of the telescope.

3 Recording Astronomical Data

The most widely used detector for optical astronomy today is the "charge-coupled device" or CCD for short. This is the same type of detector that is used in commercial digital cameras. For our purposes, all you need to know about a CCD is that is has many individual light detectors termed "pixels" that are arranged in a matrix format of rows and columns. After an exposure on a patch of sky is complete, the data from a CCD (the individual signal from each pixel) are read into a file of numbers, with each number corresponding to the signal from each pixel.

Each pixel's signal is the digitized output of an amplifier, which is linearly related to the number of photons detected by the pixel during its exposure of an image of the sky produced by the telescope. The signal has four components. One component is proportional to the light from whatever astronomical objects that were imaged on it by the telescope. A second component is proportional to the background light from the night sky that was also imaged on the pixel by the telescope. A third component is the "dark current," which is a signal caused by the thermal agitation of the holes and electrons within the CCD that grows linearly with the exposure time, and the fourth component is the zero point (or "bias" level) of the amplifier used to read out the CCD. The workings of a CCD are described in the course reference books (*e.g*. Section 6.3 of *Astronomy Methods* by Bradt and Chapter 6 of *Electronic Imaging in Astronomy* by McLean). Also, CCDs will be discussed in the course lectures later in the term.

With this very brief background, we now turn to the practical procedures used to record CCD data with the equipment that you will use at Wallace Observatory. You will gain a deeper understanding of the reasons behind these procedures as the course proceeds.

3.1 Using the CCDSoft™ CCD control program

3.1.1 Setting up the Camera

To begin taking CCD data you need to start *CCDSoft™* from the Desktop.

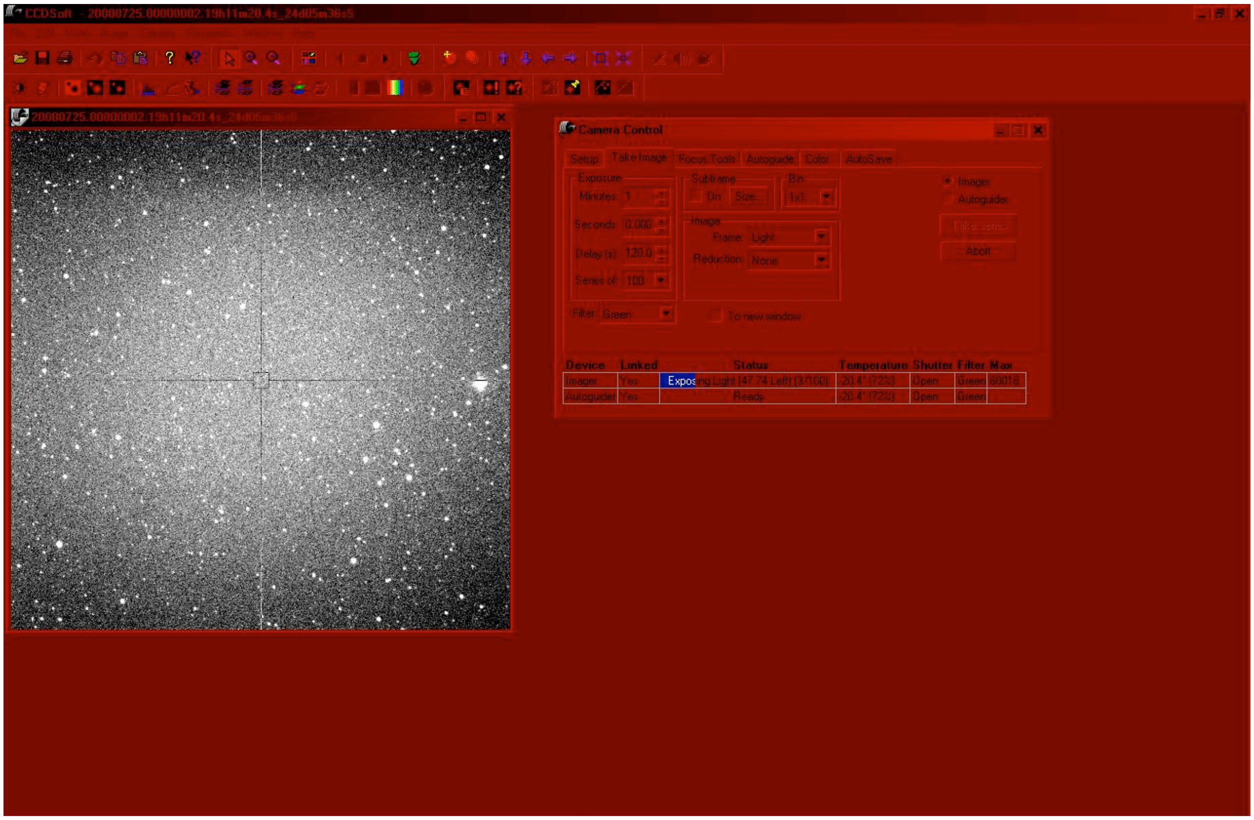


Figure 33. Taking an image while using *CCDSoft™*. The screen is red because *TheSky6™* night vision mode is being used. You can see the status bar showing the progress of the exposure, the temperature regulation, and the maximum pixel count from the last image. The Take Image tab of the Camera Control window is open, which is where you will find the options you need to set before taking an image.

1. Go to "Camera" and "Setup." A little window will pop up that looks similar to that displayed in Figure 34:

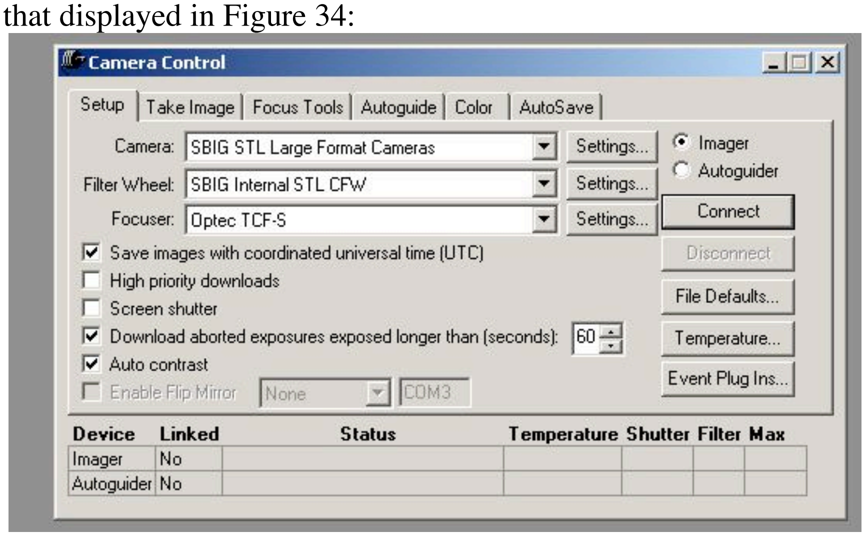


Figure 34. Camera control window in *CCDSoft™*, Setup tab. When you start the camera for the night you need to click connect and begin the temperature regulation.

2. Once the camera is connected you need to start the cooler on the camera. In the "Setup" tab, click Temperature. Set temperature regulation to on, and set it at –15 to –25 degrees C. The temperature should be set such that it can maintain a low temperature while working at 70-80% of its cooling capacity.
3. Next click on the "`AutoSave`" tab and check the box marked: "`Save as FITS files`". Make a folder to save your night of images to, and make sure the save to path goes to that folder. When you are ready to start saving images, check the box labeled "`AutoSave On`" so you will not forget to save the images.

3.1.2 Taking Images

Next click on the "`Take Image`" tab, Figure 35:

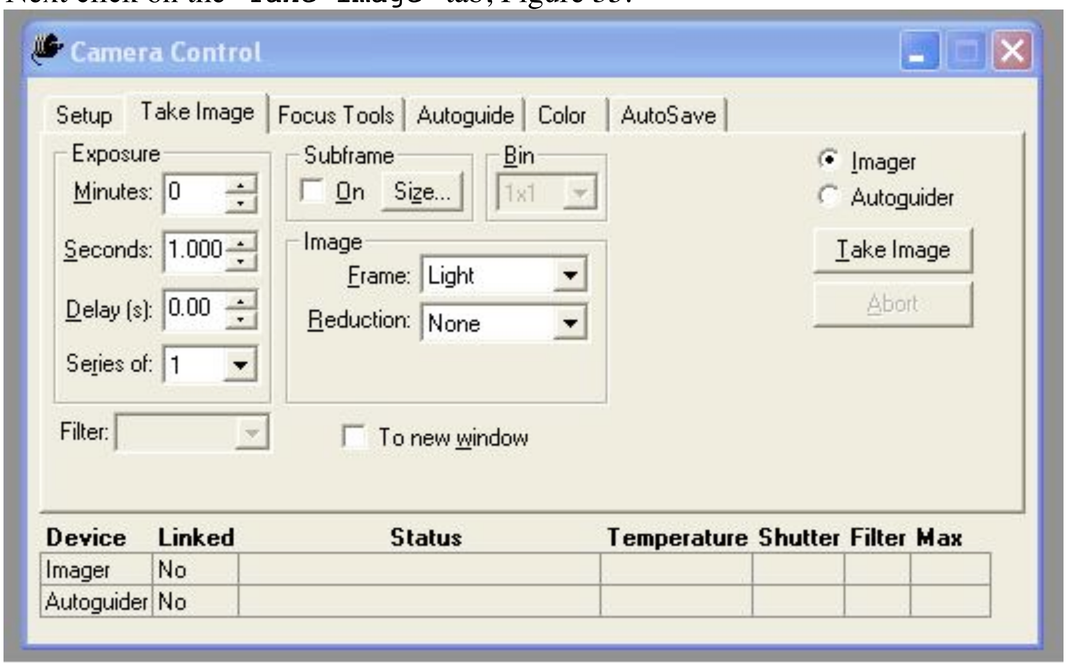


Figure 35. Camera control window in *CCDSoft™*, Take Image tab. This tab allows you to select your exposure time, the type of image you would like to collect and how you would like to bin your images. It is also the tab you use to collect images by clicking the "Take Image" button. When an image is being taken, its progress will be shown in the "Status" column, and you will have the option to click "Abort" to stop taking the image. The "Max" column will indicate the maximum count from your last image, so you can tell if it was overexposed.

The "`Image Frame`" menu allows you to select a normal "`Light`" image or calibration images, "`Dark`" and "`Bias`". We'll explain "`Flat`" sometime during the semester but we are not going to worry about this calibration for our projects. For more information on these types of calibration data, refer to Sect. 3.2.1 "Calibration data for the CCD." The "`Image Reduction`" setting should be set to "`None`" for this class. The "Autodark" reduction should never be used for this class, because your raw image will not be saved.

The “`Series of`” option allows you to take more than one image in a row without having to click “`Take Image`” each time and is very useful for sequences of exposures. You can set you exposure time in the “`Minutes`” and “`Seconds`” options.

You can select three different bin settings for your camera with the “`Binning`” button: 1x1, 2x2 and 3x3. Binning the image down from 1x1 will reduce exposure times but also will reduce the image resolution and lower the saturation point for your exposure.

Once you have focused the telescope you can start taking actual image data. Choose your exposure time and click “`Take Image`”. The CCD control box will tell you what is happening, for example: “`Exposing Light Frame (34%)`” and you will see the minutes ticking down, or “`Downloading Image`”. Make sure to turn off the computer monitor and any lights to reduce the noise it will add to images. Once an image is completed, it will be displayed on your screen. To the right of the status bar, you can check the number of counts in your star so that you make sure you don’t saturate your data.

By moving the cursor over the images, you will be able to see the pixel count in the bottom status bar. In general you want the signal from your object to be something between 10,000 and 20,000 counts, although this is very hard to get for faint objects so do what seems reasonable. By increasing your exposure time you will get more counts in your object but you will also get more counts on the sky. The inverse is true for decreased exposure time. An oversaturated image will have pixel counts of over 65,535. Exposures should not exceed 60 seconds, or inaccuracies in the telescope tracing will cause trailed images of the stars.

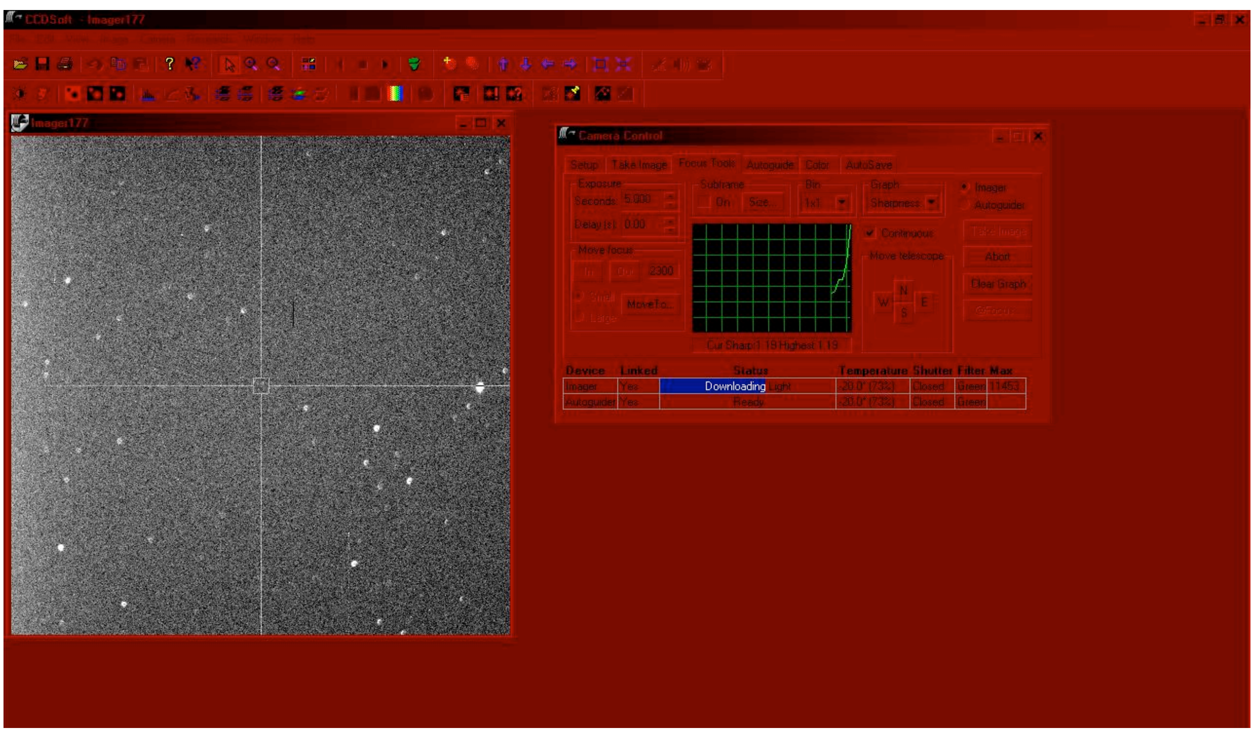


Figure 36. Sample of *CCDSoft™* Focus Tools window. @focus is running, displaying a graph of its progress in the Focus Tools tab, and the images it takes in the image window.

3.1.3 **Focusing**

The "`Focus Tools`" tab is used when you first set up with the CCD camera. You can either use the @focus feature, or manually adjust the focus with the "`In`" and "`Out`" buttons. It will take a series of images, and you can adjust the exposure time and delay.

When you select "`@focus,`" you can specify the kinds of jumps the focuser should make, and the initial direction. If you pick the wrong direction, @focus will eventually turn around. You will be able to see the images that it uses as a check to make sure it selects the sharpest image. There will also be a graph in the Focus Tools tab of the sharpness for each focus. If @focus brings the focuser all the way out or in, or if the final image does not look focused, you can run @focus again, or determine the best focus by hand. You should keep track of how the focus of your images looks throughout the night; you may need to refocus as the temperature changes and your objects move.

Astronomical Image Data

The following are three types of astronomical image data that you might want to collect for your class project. The first is the measurement of position, which is termed *astrometry*. The second is the measurement of the integrated intensity within a broad band of wavelengths, which is termed *photometry*. The third is the measurement of an object's spectrum. This measurement is termed *spectroscopy* if one is concerned only with the identification of spectral absorption and emission features. It is termed *spectrophotometry* if one is concerned with the absolute measurement of intensity as a function of wavelength. Although all the data acquired in this course will be with CCDs, the way in which the data are acquired and the calibration data need to analyze them depends on which of the three types of measurements is being executed.

3.1.4 Astrometry

Astrometry is the measurement of the position of an astronomical object within a standard reference frame. A common use of astrometric measurements is to derive orbits for solar-system bodies. To perform astrometric measurements of fixed or moving objects, one should obtain CCD frames that include not only the object of interest, but astrometric reference stars as well. Astrometric reference stars—recorded on the same frame as one's object—serve to calibrate the coordinate system.

3.1.5 Photometry

Photometry is the measurement of the brightness of a body within a broad band of wavelengths. The wavelength bands most commonly used are defined by a set of filters; the *B* ("blue"), *V* ("visual," which appears green), *R* ("red"), and *I* ("infrared") filters comprise a standard set. Absolute photometric measurements require calibration through observations of standard stars (stars of known magnitude) during the same observing session when the objects of interest are observed. However, one can make differential photometric measurements with just one or two other stars acquired in the same field as your object of interest.

3.1.6 Spectroscopy

Spectroscopy is the analysis of light by separating it out in wavelengths or colors. In this class we will do spectroscopy in the visible wavelengths, about 400-800 nm. Spectroscopic measurements require calibration with a known source; in this class we will use an argon lamp.

Spectrophotometry is a bit more complicated because you are interested in both particlar wavelengths and the intensity of your object's spectrum at those wavelengths. It is a quantitative method of studying spectra. For this you need to calibrate both the wavelength (with the argon lamp) and intensity (with a standard star) of your sources.

3.2 Calibration data

For each session in which you record data for your project targets at the telescope, you should record calibration data as well. It is necessary to calibrate the CCD, the instrument, and the Earth's atmosphere. Calibration data are essential for all astronomical measurements. The type of calibration data that you need depends on the type of astronomical measurements that you are making. The amount of calibration data that you need depends on the stability (over time) of the instrument parameters and the stability of the extinction of starlight by the Earth's atmosphere (*e.g*. perfectly steady clear conditions, or variable cirrus). Ideally, the calibration data would be recorded before you record your target data, between exposures of target data, and after you have finished recording target data. This ideal is not always achievable, since time at the observatory is limited and the weather conditions are not under your control.

We discuss separately the calibration data needed for the CCD and the Earth's atmosphere.

3.2.1 Calibration data for the CCD

For the CCD, three types of calibration data can be acquired:

Bias Frames. A bias frame calibrates the zero point, or baseline signal of the CCD electronics. It is carried out by taking an exposure of 0.0 seconds while the camera shutter is closed. If you look at a bias frame, it may contain irregularities such as cosmic ray events. These defects may be eliminated in data analysis by taking several biases at the beginning of the night and creating an average bias frame. Subtraction of a bias frame removes the average zero light, zero exposure time signal from the data, including any "hot"-pixel effects (see Figure 37 for an example of these).

Dark Frames. A dark exposure calibrates the rate at which the CCD pixels accumulate signal when no light is incident on them, due to thermal effects. The cooler the CCD, the lower the dark current. If you are using several different exposure times to for you project data, you can calibrate the dark current vs. exposure time by taking a series of dark frames at exposure times that span the range you are using. Keep the shutter closed for the dark frames. If you are using just one or two exposure times, you can record dark frames at the exposure time you are using as your light exposures; these frames will include the bias signal too. You should take a few at the beginning, middle and end of the observing night.

Flat-field Frames. At some level any CCD chip will not be entirely uniform in response. Certain pixels will be more sensitive to light than others. Also dust particles on optical elements near the focal plane (such as the filter) will cause a non-uniform response. Thus, a target focused on a certain area of the field may output a different signal than the same target focused in another area. A flat-field frame calibrates the relative sensitivity of each pixel in the CCD by exposing the pixels to an extended light source of uniform brightness. The type of flat-field (*dome* flat, *sky* flat, or *twilight* flat) you take will depend on your project; you need flat-field frames in each filter that you use for your project data on the night that you record the data.

If the zero point, dark rate, and sensitivity of all the pixels in the CCD did not change with time, then only one set of calibration data would be needed for the entire term. However, changes do occur, so more frequent recording of calibration data are needed.

CCDSoft™ makes the recording of calibration data easy. To record bias frames, change the exposure type to "`Bias`" and the exposure time to 0 seconds. Take about 5 exposures (you can use the "`Take Series`" button for this so you don't have to click to start your image each time). These will be saved in the data directory:

`/Applications/Equinox 5.3/MPjSBIG/MPjSBIGImages.`

To record dark frames, change the exposure type to "`Dark`" and take 5 exposures for each exposure time you used (again you can use the "`Take Series`" option). This is because the dark measures the thermal noise accumulated in your CCD during your exposure. The dark signal should be proportional to the exposure time. These images will be save in the directory:

`/Applications/Equinox 5.3/MPjSBIG/MPjSBIGDark.`

Several procedures can be used for recording flat fields—one can use the twilight sky or an evenly illuminated screen located near the telescope. If you are taking long exposures, or the sky is bright with moonlight, you may be able to use the night sky for flat fields. Details of the flat-field procedure that will be best for your project will be explained later by your lab instructor. Be sure you remember to port the calibration files in addition to your data at the end of the night.

3.2.2 Calibration data for the instrument

The only instrument that you may use in this course that needs calibration *per se* is the spectrograph. The calibration needed is the wavelength scale for the pixels on the CCD, which is carried out by exposing the spectrum of a gas lamp. Argon is a popular choice for the gas, since it has a significant number of emission lines at visible wavelengths. Perform your wavelength calibration early in the term, so that you can confirm that you are getting data within the intended wavelength range.

3.2.3 Calibration data for the Earth's atmosphere

The Earth's atmosphere affects your CCD frames in two ways. One requires extra calibration data, and the other does not. First, the atmosphere removes light from the direct beam coming from astronomical objects by scattering and absorption—collectively these two effects are termed *extinction* (see the course notes) and it varies with the wavelength of light. Extinction effects can be removed from the data through calibration with observations of photometric standard stars (non-variable stars with accurately known *magnitudes*). Several observations of standard stars (at different altitudes above the horizon) are needed when photometric and spectrophotometric data are recorded.

Sometimes the technique of *differential photometry* is used. With differential photometry, the standard stars are chosen to be in the same CCD frame as the object of interest. Hence the standard star data are recorded whenever an object frame is recorded, and separate standard-star observations are not necessary.

In addition to extinction, the Earth's atmosphere refracts (bends) the light from astronomical objects by a small amount that depends on the altitude of the object above the horizon. For an object at the zenith, the refraction is zero, but for an object 45° above the horizon, the refraction is about 60 arc seconds (1 arc minute). Usually the calibration of refraction is done with astrometric standard stars (stars with accurately known positions) on the CCD frame with the object of interest, so astrometric measurements require no additional calibration frames. Of course, one must be sure to have astrometric standards on the same frames as one's object.

3.3 Checklist for Observing

1. Set up the telescope with *TheSky6™* and point at a relatively bright star.
2. Bring up *CCDSoft™* , connect the camera and begin cooling it.
3. Choose "save as fits" under the AutoSave tab
4. Choose "AutoSave On" under the AutoSave tab
5. Use the "Focus Tools" tab in *CCDSoft™* to get your images focused for the star, manually focusing the telescope
6. Move the telescope to the object you want to observe.
7. Start taking data and be sure to record notes about your data collection in your notebook; a sample logsheet is provided at the end of this section.
8. Collect your calibration frames sometime during the night.
9. When you are finished collecting data, disconnect the camera and close *CCDSoft™* .
10. Park the telescope using *TheSky6*.
11. Port the data to `titania` inside the main building at Wallace and your class locker on Athena using SecureFX.
12. Choose shut down from the Start menu.
13. Turn off power strip on table and then on pier.
14. Put the cover back on the telescope.

3.4 Data Collection

3.4.1 How to Choose an Exposure Time

When you plan your observations before going the observatory, a critical issue for your plan is the appropriate exposure time. If your exposure time is too long, the image could become saturated, making it impossible to use it for photometry. On the contrary, if your exposure time is too short, you may not accumulate enough light from your source to have adequate signal-to-noise ratio (SNR) to achieve your project objectives, especially for photometry and spectroscopy projects.

Although the appropriate exposure time will largely depend on the magnitude of your targets, but it can also depend on the observing conditions. If it is a perfectly clear, moonless night, you will get a different amount of signal from a given object than if a full moon is present.

A cloudy night with a setting quarter moon will yield yet a different background level. Moonlight means more background light, you might want to increase your exposure time some. Partial clouds or dew on the telescope optics will also result in less signal, so make the appropriate adjustments as you go. Always be aware of what the environment is doing and modify your observations accordingly. Choosing an exposure time is more of a method than a standard, and it will vary for the same object from night to night, so BE FLEXIBLE with your exposure time. You'll want to experiment each night before you collect data on your source.

That being said, these are some general "benchmarks" for exposure times if you are taking images (photometry/astrometry):

* bright objects (brighter than 4th or 5th magnitude) -- 0.25 to 10 seconds
* middle-magnitude objects (6th-9th magnitude) -- 30 to 90 seconds
* faintish objects (10th-12th magnitude) -- 90 to 180 seconds

The tracking of the telescopes is good for about 3 minutes for point sources, although you can try for 4-5 minutes. Don't go longer than ~5 minutes. Remember that the magnitudes of fuzzy objects are for the integrated source (total magnitude over the whole area of object). For most of these objects you will want to take 4-5 minute exposures. Exposure time will also be filter-dependent – for instance, exposures in the B filter (or the number of images you take and add together) should be at least 2 times longer/more than for V or R filter exposures for an equivalent SNR.

The image quality or "seeing" also affects exposure time. We say that the seeing is good when the atmosphere is stable and the images are small. A highly turbulent, unstable atmosphere, produces larger images. For a given source, the image will contain the same amount of light, so that the smaller the image, the larger the peak intensity at the center of the image will be. With more light concentrated in the center, the image will reach saturation (see 3.4.2, Data Saturation) sooner than on a night, perhaps requiring you to reduce exposure times if you are near the saturation limit.

If you are doing spectroscopy you can't look at anything that is fainter than about 8th magnitude. For fuzzy things (*e.g.* galaxies) don't go fainter than about 4th magnitude. Exposure times will be approximately:

* Calibration frames (argon lamp): 30-60 seconds
* Bright source (moon, 1-3 mag object): 60-90 seconds
* Fainter sources (fainter than 3rd magnitude: 90-300 seconds

For spectroscopy projects, another easy way to make exposure time calculations is to scale your target by the successful spectra of other similar objects (i.e. If your target is a star, you could find the spectra and exposure time of another point source). If you have data for successful spectra, you can determine your own target's exposure time by scaling by a factor of 2.5 for every magnitude fainter that your target is to the reference's spectra (Kannappan and Fabricant, Sky & Telescope, July 2000).

3.4.2 Data Saturation

Data saturation occurs when there is too much signal from the target, causing the signal to reach a maximum limit, which is different from what the value of the signal would have been in the absence of saturation. Hence saturated images are nearly useless for analysis.

Three types of saturation can occur: which type of saturation will be dominant depends on the details of the electronics that process and digitizes the CCD signal. The first type of saturation occurs when the number of electrons (produced by detected photons) exceeds the "full well" of a pixel. The full well is measured in electrons. If the full well is exceeded, the pixel "bleeds" electrons into surrounding pixels up and down its columns, creating streaks along the columns. The second type, saturation of an electronic amplifier in the signal processing chain, may occur first. The symptom of this type of saturation is several pixels at the same number—say 10233—and no pixels with a greater number. The third type of saturation is digital. The diagnostic of digital saturation is having pixels with a signal of $2^n - 1$, where n is the number of bits used by the analog-to-digital converter in the CCD electronics. Common values for n are 16 bits and 14 bits, for which you will see a lot of pixel signals equal to 65,535 and 16,383, respectively, if digital saturation is occurring.

Although you can detect cases of severe saturation by looking at the image, it is difficult to detect cases of mild saturation in this manner. Rather, there is a method to check for saturation by examining the numerical values of the pixels. Use the "Display" tab in EquinoX and hover over the image with your mouse where you want to check the values. You want about 30,000 counts (10-20,000 is okay too for fainter sources, saturation is 65,535 counts, assuming binning of 1x1) on your target.

3.4.3 Checklists for specific project types

Astrometry Checklist

1. Choose your target.
2. Create a finder chart and locate the object with your telescope. Make sure there is more than one other star in the field with your object (or the parent planet if you are look at a satellite).
3. Focus.
4. Determine the exposure time to get well exposed images of the stars you want. If you click on the display tab and look at the values, you will find out how much signal you are getting for any given exposure time.
5. Take 5-10 images on your object and save them. Make sure you have clicked the “save as .fits” button so you get them in the correct format.
6. It is critical that you record the start time and exposure time in your log book (as a check on the values in the header). From these you can derive the mid-time of the exposure, which will be used in your astrometric analyses later.
7. Do this every 20 minutes for a few hours, and on two-three nights, preferably over a few days or weeks. The time interval will vary depending on what type of object you are measuring. Use the “R” filter for your images.
8. Take bias and dark CCD calibration data.

Photometry Checklist

1. Choose your target.
2. Create a finder chart and locate the object with your telescope. Make sure there is at least one other star (two is preferable) in the field with your object.
3. Focus.
4. Determine the exposure time necessary to collect the information you want (see 3.6.1 - How to Choose an Exposure Time).
5. Take 5 images on your object and save them. Make sure you have clicked the "save as .fits" button so you get them in the correct format.
6. Take sets of images constantly for 2-3 hours (or longer on an asteroid if you have the time), you might want to switch back and forth between "V" filter and "R" filters taking 5 images in each every time.
7. Take bias and dark CCD calibration data.
8. Take standard star data a few times through the night (at least twice, preferably more often, depending on the sky conditions).

Spectroscopy Checklist

1. Choose your target.
2. Create a finder chart and locate the object with your telescope. You need to put your object in the centre of the black circle in the eyepiece (when it is there you will not see any light from the object by eye.
3. Determine how long a picture you need to take to collect the information you want (see 3.6.1 - How to Choose an Exposure Time). If you click on the display tab and look at the values you will find out how much signal you are getting for any given exposure time.
4. Take 5-10 spectra on your object and save them. Make sure you have clicked the "save as .fits" button so you get them in the correct format.
5. Take bias and dark CCD calibration data.
6. Take argon lamp calibration data a few times through the night (at least at the beginning and end of your observations).

3.5 Assessing Your Raw Data at the Telescope

It is important to assess your data after taking your first few exposures of the night, so that you can catch any subtle problems early on. Many students have wasted a good night of observing because they did not check for or were not aware of certain issues, and end up with unusable data. Some common problems are (i) out-of-focus images, (ii) cloud cover, (iii) trailing, and (iv) saturation.

3.5.1 Focusing the CCD

It is imperative to focus the CCD before taking data. Poor focusing unnecessarily degrade the resolution of your data, making them less sensitive to faint objects because of the smearing. The focus can be so poor that the data are unusable, depending on the brightness of the object and the density of stars in the field. The following is an example of unfocused and focused data, both before and after calibration. This should help you to recognize the signs of poorly focused data and how to correct them before it's too late.

Unfocused Images:

Figure 37 Unfocused image before calibration. The doughnut-like appearance of the three comparison stars are a strong indication that the CCD needs to be focused. This does not mean that you can simply look through the eyepiece and turn the focus knob on the telescope until it seems in focus. Rather, you must focus the CCD using images that you examine displayed on the computer.

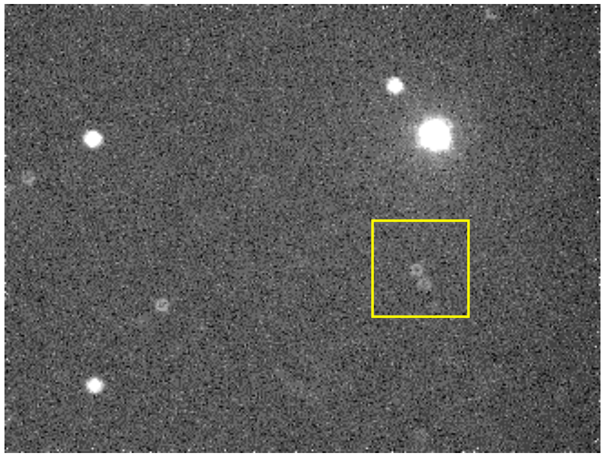


Figure 38. Unfocused image after calibration. By subtracting an average bias frame, the hot pixels (defined below) are now eliminated, revealing much fainter stars. Although the comparison stars now seem in focus, the doughnut-like appearance of these fainter stars are strong indicators that the image was *not* in focus when it was taken. This image can still be used for photometry and astrometry of the brighter, isolated stars, but not for stars that are close together. For example, the boxed stars are nearly blended together, disallowing them to be used for differential photometry or astrometry. Images of Delta Scuti and 3 comparison stars, taken with Telescope 4 on July 25, 2007 at 05:16 UT

Now that we have seen an example of an unfocused image, before and after calibration, let's look at focused images, and what you should be aiming for while taking data.

Well-focused Images

Figure 39. Focused image before calibration. This image was taken after focusing the CCD. You can tell that the image is well-focused because the target and three comparison stars now all appear as sharp images rather than doughnuts. The fainter blemishes are more distant stars, while the white speckles are again, hot pixels, and will be removed upon calibration. If you look closely enough, you will be able to see the same hot pixel patterns in this image with the uncalibrated image on the previous page.

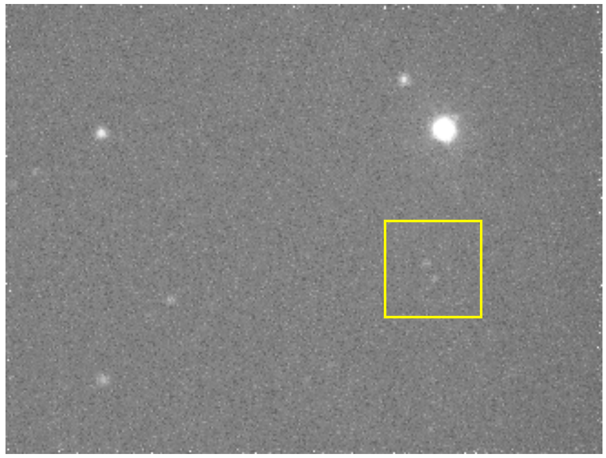


Figure 40. Focused image after calibration. Among other things, calibration removes hot pixels. You can verify that this image is well-focused by the crisp appearance of all point sources in this frame. The two fainter stars which were previously almost blended together are now well defined. These two stars, along with every comparison star in the frame, may now be used for astrometry or differential photometry. Images of Delta Scuti and 3 comparison stars, taken with Telescope 4 on July 25, 2007 at 05:16 UT.

As you can see, focusing the CCD is extremely beneficial to data analysis. A well-focused image such as the one above is a more accurate representation of the sky than an unfocused image. Thus, if your analysis yields results which you do not expect, you at least know that it cannot be attributed to poor focus.

Tip: It is a good idea to focus the CCD multiple times during the night because the temperature of the telescope changes, which will cause it to change focus. Consequently, objects can go out of focus very easily.

3.5.2 Hot Pixels

Hot pixels are disfunctional pixels on the CCD that have very large signal values. The white speckles in the uncalibrated image above were identified as hot pixels because of their consistent pattern from image to image, and their high values (significantly higher than the normal pixel value). Generally, hot pixels may be ignored during observation provided that you take enough calibration images for their removal, but you should recognize them while observing.

3.5.3 Cloud Cover – When is it too much?

Suppose you arrive to the observatory and it's a relatively clear night, with only a few wispy clouds in the sky. The clear sky clock tells you that it's supposed to become increasingly cloudier later in the night, although for now, the cloud cover does not seem thick enough to affect data-taking. But when will it become too cloudy? When the cloud cover is gradually increasing like this, it is difficult to say. As you will see, it is often necessary to take as many images as you can and then calibrate the data back in the lab in order to see how greatly the data were affected by clouds. Generally speaking, thick clouds will affect the data regardless, whereas the effects of thin clouds or minimal atmospheric moisture are much less. The following are two examples of uncalibrated images taken twenty minutes apart on a night like the one described above.

Not too much cloud cover:

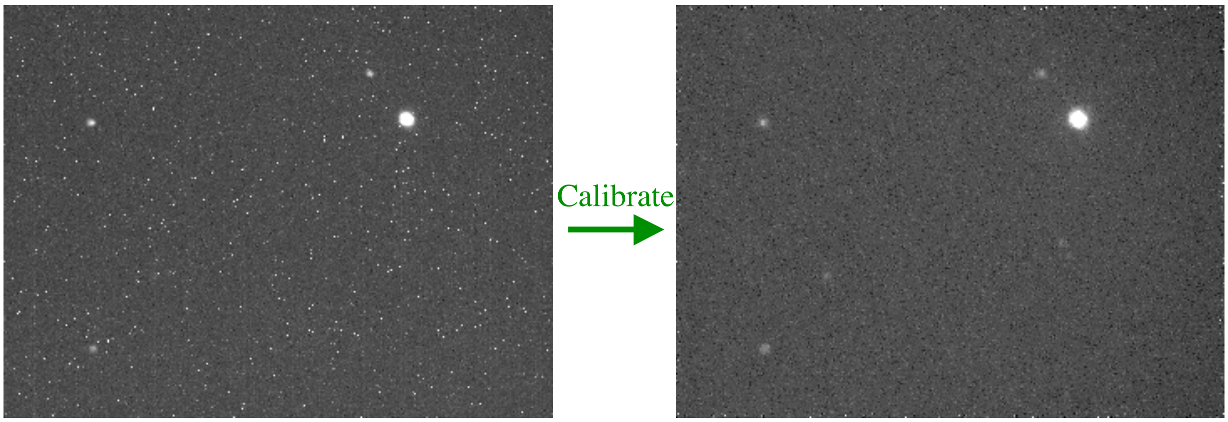


Figure 41. Image of Delta Scuti before and after calibration with minimal cloud cover. Data taken on Jul. 25, 2007 at 04:04 UT, through some wispy clouds. The uncalibrated image does not seem too affected. Although dimmer, most of the stars are seen. After calibration, the image looks very clear. The appearance of fainter stars indicate that cloud cover was not too thick.

Too much cloud cover:

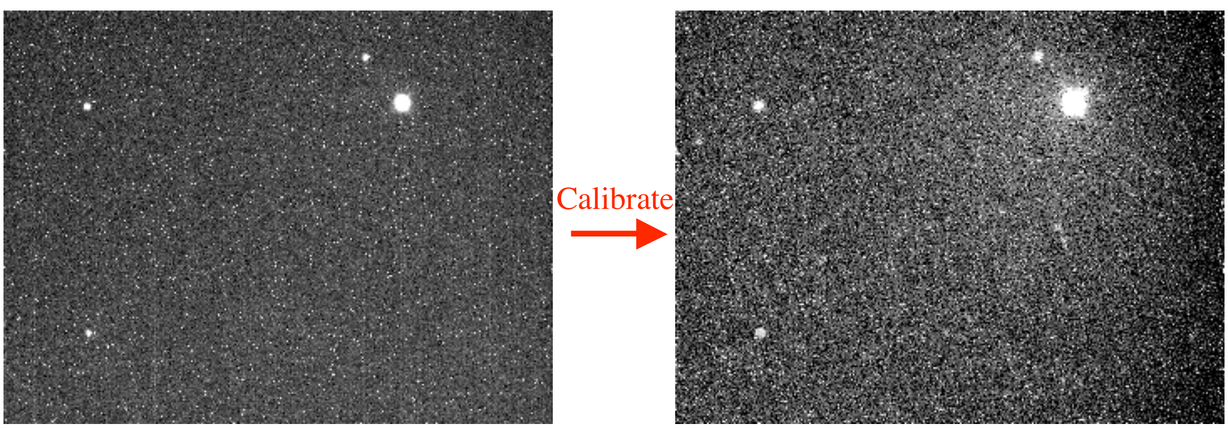


Figure 42. Image of Delta Scuti before and after calibration with too much cloud cover. Data taken on Jul. 25, 2007 at 04:24 UT, through more significant cloud cover. However, after calibration, the image shows a high noise level, indicating that significantly less starlight reached the detector than without the clouds. This is the effect of significant cloud cover, considerably reducing the signal levels from the stars relative to the noise. Analyses of these data will yield less useful results than frames recorded when clouds are absent.

As you can see, cloud cover is constantly changing - as quickly as the clouds come, they may go, too. Consequently, vastly different images can be taken even 20 minutes apart.

However, never completely give up on observing if the cloud cover is minimal. As seen above, you could still end up with acceptable data. Note that you may get away with significant cloud cover if you are doing differential photometry, since cloud thickness should not vary much within one frame. As long as you are getting good images of your object and comparison star, the data will be useful.

3.5.4 Trailing Images

Trailing is the severe elongation of a target as it appears on an exposure. Although this may occur for long exposures because of imprecise telescope tracking rates, shorter exposures (60 seconds or less) should not have any trailing. Trailing usually occurs when the telescope has had some sort of tracking error, or the telescope is knocked, causing it to shift out of place, creating streak marks.

Trailing is very easy to identify, but not often easy to correct. If there was trailing because you accidentally knocked the telescope during an single exposure, you simply need to readjust the telescope to center the target, and continue taking data. If there was trailing due to an intrinsic tracking problem of the telescope (identified by continual trailing over several short time exposures), there could be any number of problems, including weight imbalance, or telescope alignment. This kind of trailing is more severe, but can be easily fixed if you act quickly.

Tips: Take a few single test exposures at the beginning of each observing run before taking your calibration images to make sure there are no intrinsic problems with the telescope. If there are any, notify your TA. Also, do not touch anything when the CCD is exposing - the telescope is very sensitive to any slight pressure on it.

Here are two examples of trailing for different reasons:

Figure 43. Data taken on Sep. 28, 2006 at 02:25 UT. Asteroid Iris and a comparison star. Trailing due to bumping of the telescope while it was taking an exposure, on Telescope 2 (an automated GO-TO telescope), producing double images.

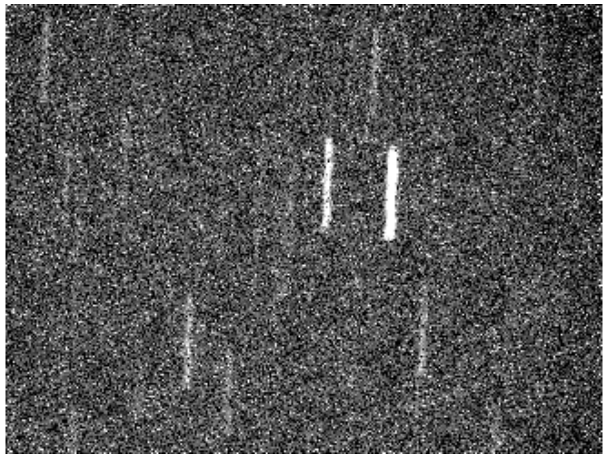


Figure 44. Data taken on Jul. 24, 2007 at 03:39 UT. Dwarf cepheid Delta Scuti and a few comparison stars. Long trails due to improper sidereal tracking rate. It was found later that there wasn't enough counterweight on the barrel of the telescope to allow correct for tracking. Grainy background is mainly due to significant cloud cover.

3.6 Data validation

Once you have recorded data, you want to be sure that your files actually contain the data, and that the data are what they should be. Your first test is to make sure that the signal you are recording in the images is what you expect (use the information in *CCDSoft™* to check the counts in your images.) Additional procedures for validating your data are described below.

Before continuing with observations, take a few test images of your object and go through the corresponding data validation checklist. It is extremely important to go through this checklist, or the data you collect may be considered "bad data." Consequently, the night of observing will be wasted.

3.6.1 Astrometry/Photometry Data Validation

1. Compare your finder charts with the view in the finderscope and camera. Although the view in the finderscope and camera may appear inverted or rotated due to the mirrors in the telescope, they should still completely correspond with your finder charts.
2. Focus the image using your target or a star in the same CCD frame. Your star profile should have a defined peak.
3. Check for saturation by looking at the "Max" column in the Take Image tab and reading the number of counts, or by moving the mouse over an image and reading the counts displayed in the bottom toolbar. With this number of counts, use the following table to assess whether the exposure time is reasonable. If not, adjust the exposure time

accordingly. A longer exposure time will give you more overall counts (in both your target and background).

4. Ensure that there is minimal trailing in your images. If there is, your telescope may have tracking or weight balance problems. Alternatively, try to focus or adjust the exposure time until objects appear as point sources (or as close as possible) without saturating the image. See Section 3.4.2 for more details.

3.6.2 Spectroscopy Data Validation

1. Make sure the light that comes through is penetrating the correct part of the fibers.
2. Compare successive images. Are there any outstanding features in one image but not the other? This may be a blemish and that image cannot be used in data analysis.

3.7 Log sheet

Date:________________________

OBSERVER(S):___________________ WEATHER:____________________

TELESCOPE: 1 2 3 4 FOCUS:_______________________

PROJECT:____

FILE NAME	OBJECT	TIME	EXPOSURE TIME	FILTER	NOTES

4 Porting Data

4.1 To the observatory data archive computer (titania)

In order to access your data from campus, you need to put it onto a computer that is always running and has a network connection to campus. This machine is our Wallace server called "TITANIA". It resides on the rear computer table inside the main building at Wallace and is accessible via a secure connection from any Athena computer on campus. The shed computers are always turned off when we close up the shed so anything left on these machines are only accessible to you during your lab section. To transfer data from machines running Mac OSX do the following. For Windows XP machines such as those controlling the Paramount MEs, see the next section.

1. Select "`Go`" from the menus at the top of your shed computer. Type `titania.mit.edu` at the prompt, or select it from the list of saved computers (Figure 45).

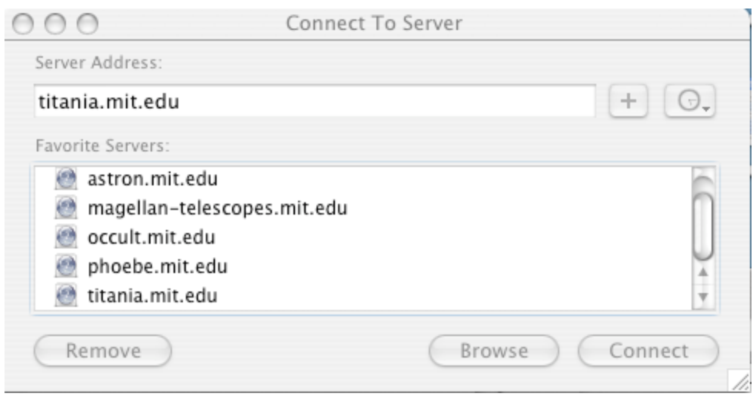


Figure 45. Sample of the window for connecting to a server with MacOSX. See text for step-by-step connection instructions.

2. Type in the user name: `students`
   and password (ask your lab instructor if you don't know it)
3. select the `"Data"` volume to mount.
4. Change to the directory:
   `/Volumes/Data/Classes/12.410-2008/`
5. Create a folder with your Athena login in which to store your data:
   `/Volumes/Data/Classes/12.410-2008/username/`
6. Find the folder on your machine that contains your data from the night and move your calibration files into your image file directory.
7. Select these and drag them into your image folder on titania.
8. Drag your folder from the images directory on your shed computer to your directory. Be sure you have copied both your image data and your dark and bias calibration data (which after the previous step should all be in the folder titled by your date of observation).

4.1.1 Data transfers with SecureFX

To transfer data from computers running Windows XP (all Piers and 16-inch during 2008), open SecureFX from the Desktop icon. Find your folder in titania as described above, and drag your files from the night into that folder. Close the SecureFX window to log out.

4.2 *To the class Athena locker: Secure File Transfer Protocol* (`sftp, scp`)

Now that you have transferred your data to the disk TITANIA, you can access it from campus. Data on TITANIA should remain there until the end of the term, barring any unforeseen problems. However, your primary data storage should be your Athena account, so you should transfer it there at your earliest opportunity (before leaving Wallace for the night is recommended, if time permits). This way you will be all set to reduce your data the next time you go to work on your project. In addition to your computer in the shed, the data transfer can be done from the computers inside the main Wallace building, or any Athena machine (as described in the file transfer section of chapter 5).

4.2.1 Data transfers with sftp

Go to the dock (bottom of the screen) and click in the "`X11`" icon. This will open an x-term window on your computer. Change directories to the location of your images on your local (shed) machine.

On a shed computer:

```
[WAO1:~] wallace% cd /Applications/Equinox 5.3/MPjSBIG/MPJSBIGImages
```

On titania:

```
[TITANIA:~] titania% cd /Volumes/Data/Classes/12.410_2008/username/
```

Connect to Athena with sftp:

```
[TITANIA:~/Public/username] titania% sftp username@athena.dialup.mit.edu
Connecting to athena.dialup.mit.edu...
username@athena.dialup.mit.edu's password:
```

Type in your password. Once you are logged in, change the directory on Athena so you are located where you want to put your data:

```
sftp> cd /mit/username/12.410-data/
```

Check that you ended up where you wanted to be:

```
sftp> pwd
Remote working directory:
/afs/athena.mit.edu/user/u/s/username/12.410-data
```

(Change the "u/s/username" in the above line to your appropriate destination, such as "j/r/jruser" for the username jruser, or "other/username" if one of the first two characters of your username is not a letter.) If you want to create a new folder here you can do so with the `mkdir` command then `cd` into your new directory.

```
sftp> mkdir 2008-09-22
sftp> cd 2008-09-22
```

Put (all) your images onto Athena; here the "`*`" is used as a "wildcard," which matches any group of characters:

```
sftp>put *
Light_NXXX_B1+0C_30S0-1.fits         100%  640KB  43.8KB/s   00:13
```

For example, if you just wanted to put only some of your images in your Athena locker—say all the files whose names begin with "`Light`" and end with "`.fits`" (with any group of characters in between), you would type:

```
sftp>put Light*.fits
```

Once your data are all there, type “`bye`” to leave sftp:

```
sftp>bye
```

4.2.2 Data transfers with `scp`

As an alternative to `sftp`, you can use another command called `scp`, with which you can carry out the data transfer in a single command line. On Athena make sure you are in your `12.410-data` directory (`/mit/username/12.410-data`).

```
athena% scp -r titania@titania.mit.edu:/Volumes/data/Classes/
12.410_2008/username/ .
```

(type in your password at the prompt)

`-r` means “recursive” and will copy all the folders in the stated directory to where you are on Athena. Make sure you have the ‘`.`’ at the end, this where you are copying your data to, in this case your 12.410-data directory. If you are not in your data directory you can execute the above command in a slightly different manner (all on one line) to get the same result:

```
athena% scp -r
titania@titania.mit.edu:/Volumes/data/Classes/Data/12.410_2008/usernam
e/ /mit/username/12.410-data/
```

Additional Notes:

Most normal `xterm` commands (`cd`, `pwd`, `ls`, `mkdir` etc.) work in `sftp` and refer to changes on the computer to which you are connected. If you need to change locations or get information for files on your local machine while using `sftp`, put a “!” before the command (for example, `!pwd)`. The only command that does not use the “!” is `cd`, for this command you use “`lcd`” (local change directory).

4.2.3 At Wallace: from the shed computer directly to your Athena locker

Before getting back to campus, you may wish to transfer your data from a shed computer directly to your Athena locker, so you do not have to worry about transporting it later. This is very useful to do at the end of an observing night, especially if you are waiting for others to finish, because it will save time for later. To do so:

1. On a shed computer, open a terminal window. Type: “ssh username@athena.dialup.mit.edu” or “ssh username@linux.mit.edu”, where “username” is your Athena Kerberos name. It will prompt you for your Athena password.
2. Create a folder on your Athena locker by typing: “mkdir 12.410-data”.

3. Open a second terminal window on the shed computer. Locate the files you want to copy by navigating through the folders ("cd foldername" takes you to that folder). Navigate to the folder which contains all of the files you want to transfer to Athena.
4. In this second terminal window, type: "scp * username@athena.dialup.mit.edu:." It will prompt you for a password to your Athena account. The * is a wildcard character standing for any combination of any characters. Thus the command in the previous sentence will copy every file in that folder into your Athena locker. You should see the transfer start to occur in the terminal window.
5. Once the transfer is completed (which may take awhile if you have many files), you may view your files in your Athena locker by going to the first terminal window and typing, "ls". This lists the files in your Athena locker. You may move them to the folder you created in step 1 by typing "mv filename 12.410-data".

5 Computational Tools for Data Reduction and Analysis

5.1 Operating Systems

This tutorial will give you the bare minimum you need to get started in this class. General UNIX commands are introduced, and all the examples given pertain to either working with your project data or with files for a problem set later in the class. Documentation for the basic Athena shell commands such as `cd, ls, more`, etc. are found using the `man` command. This command (*e.g.* "`man cd`") will bring up a description of the command and any options available for use with the command. Further descriptions of this command are described in the section below entitled: "The UNIX manual".

5.1.1 UNIX and Linux at MIT

On the MIT campus, Athena is our server, a UNIX system. UNIX is a suite of programs that form the foundation of our computer network for workstations and multi-user servers. On Athena, X-terminals provide a graphical interface between the user and UNIX. The UNIX operating system is made up of three parts; the kernel, the shell and the programs.

The kernel of UNIX is the center of the operating system: it allocates time and memory to programs and handles file storage and communications in response to system calls. The shell is the interface between the user and the kernel and is started when you log into the computer. The shell is a command line interpreter. It interprets the commands that you, the user, type and arranges them so the computer can carry them out. The commands are themselves programs: when they terminate, the shell gives the user another prompt (% on Athena). Finally, everything in UNIX is either a file or a process. A process is an executing program identified by a unique process identifier. A file is a collection of data. You create files whenever you run a text editor, compile code, save an image, etc. These files are stored in directories.

5.1.2 Athena

Log in to Athena

Ask a lab instructor if you are unsure how to do this.

Attach the course locker:

The 12.410 "locker" is a collection of directories mounted under the basic directory name `/mit/12.410`. In order to work with files in this directory, you need to add the 12.410 locker to your path. In any *xterm* or *terminal* window of your Athena screen, type the `add` command to add the course file locker to your computer.

```
athena% add 12.410
```

(Use `add` here instead of `attach` because you want software that is in the 12.410 locker to be accessible in your path.)

Changing directories on Athena

Next, to change from your home directory to the class directory, you need to use the "`cd`" command:

```
athena% cd /mit/12.410
```

Now you can change your working directory to the `student` subdirectory in one of two ways. (1) with the `cd` command: you can specify a full "pathname", the entire directory path starting at the first slash (`/mit/12.410/student`), or (2) since you are in the directory just above student you can just type in "`student`" to move into that directory.

```
athena% cd student
```

In this case it is equivalent to:

```
athena% cd /mit/12.410/student
```

If you are in the student directory and want to move to the directory above you can use the command:

```
athena% cd ..
```

where the ".." refers to the parent directory of the current working directory. Note that "." refers to your current working directory, and "/" refers to the "root", *i.e.* the top of the directory structure in a UNIX file system. These shorter forms allow you to move between directories in a relative fashion. For example, if you are in "Public" and want to go to the examples directory in the "student" subdirectory, you would type:

```
athena% cd ../student/examples
```

In any location, you can list the files and subdirectories within that directory with "`ls`":

```
athena% ls
12.411    Public    idl_libs  software  www
OldFiles  arch      ops       student
```

12.410 set-up script on Athena (RUN THIS ONLY ONCE!)

Now that you understand a little about changing your working directory in UNIX, you need to set up some directories for your work in this class. To do this you will to run a special script on Athena. This should only be run ONCE!

```
athena% setup 12.410
```

This script will do the following:

1. Create a `12.410-data` directory in your home directory in which to store your data.
2. Give 12.410-staff permission to read and write in that directory.
3. Make a link to that directory in the /mit/12.410/student directory.

The net result is that you can `cd` into: `/mit/12.410/student/username`, and put all of your data there. Then you can carry out your reduction and analysis work there as if it were in the course locker, but everything will actually be stored in your Athena home directory data space.

Now that you have set this up, make a new directory called "`Tutorial`" in your student directory for the class with the command "`mkdir`".

Change your working directory to the one that you just created:

```
athena% cd /mit/12.410/student/username
athena% mkdir Tutorial
athena% cd Tutorial
```

You can check where you are by using the `pwd` (print working directory) command, however, you should be aware that `/mit` is generically an alias for a variety of remote file paths, so if you have done everything correctly you should get something like the following, except for your user path.

```
athena% pwd
/afs/athena.mit.edu/user/s/u/susank/12.410-data/Tutorial
```

In normal use, you can substitute "`/mit`" for "`/afs/athena.mit.edu/course/12`" anywhere you encounter it for this class (that is, if you remembered to attach the course locker as described above).

The UNIX manual

If you want a complete definition of any command in UNIX, you can use the `man` command. Its argument is the UNIX command that you want defined. Examples for `cd` and `ls` are:

```
athena% man cd

--------------------------

User Commands                                          cd(1)

NAME
     cd, chdir, pushd, popd, dirs - change working directory

SYNOPSIS
     /usr/bin/cd  [ directory ]

  sh

     cd  [ argument ]

chdir  [ argument ]

  csh

     cd  [ dir ]

     chdir  [ dir ]

     pushd  [+n  | dir ]

     popd  [ +n  ]

     dirs  [ -l ]

  ksh

     cd  [ arg ]

     cd old new


  /usr/bin/cd

     The cd  utility will change the  working  directory  of  the
     current  shell  execution  environment. When invoked with no
     operands, and the HOME environment  variable  is  set  to  a
```

```
     non-empty value, the directory named in the HOME environment
variable will become the new working directory.

sh

     The Bourne shell built-in cd  changes the current  directory
     to  argument.  The shell parameter HOME is the default argu-
     ment. The shell parameter CDPATH defines the search path for
     the  directory  containing  argument.  Alternative directory
     names are separated by a colon  (:).  The  default  path  is
     <null>   (specifying  the  current  directory).  Note:   The
     current directory is specified by a null  path  name,  which
     can  appear  immediately after the equal sign or between the
     colon delimiters anywhere else in the path list. If argument
     begins with `/', `.', or `.. ', the search path is not used.
     Otherwise, each directory in the path is searched for  argu-
     ment. cd  must have execute (search) permission in argument.
     Because a new process is created to execute each command, cd
     would be ineffective if it were written as a normal command;
     therefore, it is recognized by and is internal to the shell.
     (See pwd(1), sh(1), and chdir(2)).
--------------------------
```

To find the full definition of the command:

```
athena% man ls
```

You can even find out more about the `man` command itself:

```
athena% man man
```

File Transfer

Only "secure" file transfer connections are allowed to Athena and to most other computers as well. File transfer protocols will be needed to move the data you collect at the telescope from Wallace to your directories on Athena for analysis. File transfers from the data computers (which are Macintosh computers) to Athena will be handled via secure `sftp` with the Macintosh command line interface, described previously in the section: To the class Athena locker: Secure File Transfer Protocol (SFTP) and at the web location:

```
http://web.mit.edu/is/help/ftp/
```

For this tutorial, you will simply copy sample files from the examples directory to your personal directory using the `cp` command.

```
athena% cp /mit/12.410/student/examples/UT20021021/* ./
```

In the above command, the "*" is a common 'wildcard' that means "match any set of characters." In the current context, it is a way of specifying the names of all files and subdirctories in the given location `"*.fits"` would specify all files ending in `".fits"` The "**./**" (or simply a ".") refers to the current working directory, so the `cp` command copies all files from the UT941004 directory into the current directory which should be your Tutorial directory. Check the results of your copy with the `ls` command.

```
athena% ls
ps5-01.fits  ps5-03.fits  ps5-05.fits  ps5-07.fits  ps5-09.fits
ps5-02.fits  ps5-04.fits  ps5-06.fits  ps5-08.fits
```

If everything went correctly, you should see the listing above.

5.1.3 Macintosh

The layout and components of files on machines running MacOSX are called the file system and often referred to as the "finder". It consists of a series of files and folders and you can invoke a terminal window or an X Window that recognizes the same commands as one uses on UNIX (`cd, pwd`, etc.). The top level of the files system is called the "`root`" directory and can be referred to with a "`/`" (as described above). Other directories are branched from the root like a tree. User information and files are stored in `/Users.` `/System` is for various system files used by the GUI, and all MacOSX applications, and user programs are stored in `/Applications`.

MacOSX also has a convenient windowing interface such that you can launch a program by clicking on its icon in the "dock" located on the bottom of your screen. Programs that don't have "shortcuts" or links to the application file can be found in the `/Applications` directory and launched by clicking on the appropriate icon in the appropriate folder. You'll learn a bit more about specific programs throughout this manual.

5.1.4 Windows

Windows is an operating system with which you may already be familiar. It has a similar interface and functionality to MacOSX as discussed above, but it is not based on the UNIX operating system.

5.2 Creating Text Files

During several phases of data reduction, you will need to make and edit "text files" in order to provide the computer with information it needs to continue your processing. A text file is just that: a file with nothing in it but normal letters, numbers and other standard typewriter characters (and the spaces between them). The data files you just transferred are binary files and contain special characters that do not appear on a keyboard.

The simplest way to deal with text files on Athena is to use `emacs`. To open an `emacs` window, use the command `emacs` as follows. (The & in the following command essentially tells the current window to stay active and not transfer its control to the new `emacs` window.)

```
athena% emacs &
```

When the new window comes up, you can click in it, and type in it. Anything you type there will stay in that `emacs` "buffer" until you quit the program, but it will then vanish. To save it as a file (a textfile, no less), type `Ctrl-x Ctrl-w` (`C-x` indicates `control-x` and is typed by holding down the "`Ctrl`" key and typing "`x`" while it's down). It will then prompt you for a file name down near the bottom of the `emacs` window. Type in a name for your file. You can quit `emacs` by typing: `Ctrl-x Ctrl-c.` To see what is stored in your new text file use the `more` command.

```
athena% more filename
```

If you wish to later edit the file, simply open it again in `emacs`.

```
athena% emacs filename &
```

Make whatever changes you need to make and type `Ctrl-x Ctrl-s` to save your changes, then `Ctrl-x Ctrl-c` to quit again.

For in-depth tutorials on basic computing skills and access to more help information than is presented here, the teaching staff encourages you to examine Athena On-Line Help (OLH). This web page contains pointers to numerous references and locations of additional sources of help. It is located at the URL:

`http://web.mit.edu/olh/`

5.3 *Environments*

There are a number of environments that might be used for analyzing your project data including *IDL*, *Mathematica, MatLab*, and *IRAF*. The class software has been written in *IDL* and is described in detail below. The other environments are introduced so you can be aware of what various astronomers may use, however, further instructions are not provided in the manual. If you already are familiar with the environment, you are welcome to work in it. The teaching staff can answer basic questions; however, the teaching staff does not support instruction for new users.

5.3.1 Interactive Data Language *(IDL)*

Getting Started

Interactive Data Language *(IDL)* developed by Research Systems Inc., or RSI, is a commercial software package that requires a license for use. It will be used for most of the image processing and data reduction we do in this class. This document explains how to access *IDL* from any Athena (Sun) workstation and outlines the basic commands to be used in *IDL*. This short tutorial only scratches the surface of the capabilities of *IDL*, but will give you enough background to run the tasks for this class. *IDL* is kept in a separate Athena locker called `envi`.

Commands in IDL

To use a UNIX command from within *IDL*, put a "`$`" before the command. Hence to list the files in your working directory, you type:

```
IDL> $ls
```

The `$` tells the computer that the command is to be run outside of the *IDL* interface. The only UNIX command that works the same inside and outside of *IDL* is "`pwd`" – print working directory.

In *IDL* single quotes are used to denote strings. The name of a directory is a *string*, which is enclosed within two single quotes. The change directory *IDL* command is `cd`, and it is separated from its argument (as are all *IDL* commands) with a comma:

To change directory type:

```
IDL> cd, 'newdirectoryname'
```

If you do not know the path name of the directory to which you wish to change, you can get a dialog box to search for the directory in a dialog window with the command:

```
IDL> cd, dialog_pickfile(/dir)
```

Command Line editing

`arrow keys`	moves the cursor as you expect
`Ctrl-e`	moves the cursor to the end of the line
`Ctrl-a`	moves the cursor to the beginning of the line
`Ctrl-k`	deletes the rest of the line
`Backspace`	deletes the character behind the cursor
`Ctrl-s`	prevents the cursor from responding to keystrokes
`Ctrl-q`	returns the cursor to normal function if you accidentally hit Ctrl-s

Getting out of an *IDL* procedure if it gets stuck or you make a mistake

`Ctrl-c` will essentially kill the process you are running, however, after using `Ctrl-c` you want to make sure *IDL* is not stuck in the middle of a procedure. You do this by resetting *IDL* to the main level:

```
IDL> retall
```

This means "return all". Whenever things look weird in *IDL*, type retall.
If things completely hang up you can do a hard reset of *IDL* without exiting by typing:

```
IDL> .reset
```

Help menu

If you want to know more about a command or want to see if a command exists to do something type a question mark at the prompt.

```
IDL> ?
```

This will bring up an interactive help window (run through acrobat reader) that will allow you to search in either the index or contents of *IDL*'s online help book.

Start *IDL*

Now that you know a little about the command structure in the *IDL* environment you are ready to actually load the program. To load *IDL*, the following commands need to be executed:

```
athena% add 12.410
athena% source /mit/12.410/student/idl_12.410
athena% cd /mit/12.410/student/username
athena% idl
```

After executing these commands, you should see some initial messages from the software, and then a new prompt:

```
athena% idl
IDL Version 6.2, Solaris (sunos sparc m32). (c) 2005, Research
Systems, Inc.
Installation number: 98172-22.
Licensed for use by: MIT

        ***************NOTE FOR Solaris USERS*******************
        The Motif library supplied by Sun in Solaris 8
        requires a patch, available free of charge from
        http://www.sunsolve.sun.com, before it will work properly
        with IDL. Without this patch, editable text and table widgets
        may cause the IDL program to crash. The patch number is
        108940-23, for both 32 and 64-bit Sparc platforms.
        ******************************************************
 IDL>
```

This means that *IDL* is running.

Displaying an image

IDL has a collection of useful tools for image display and processing, however, you need to understand what the tools are doing incase the default parameters don't give you what you expect. We are going to start with the simple task of displaying an image and playing with the display scale. There are some programs inside *IDL* that make this easy, but we want you to understand the basics of what the programs are doing. We have written tools to help you with the data analysis for your projects specifically, but they will be covered in more detail in section 6, "Reducing Your Data".

First you need to read an image. "`FITS`" files have two pieces of information in them, (1) the image itself (which is binary in nature) and (2) supporting information about the file, called the header (which is asci in nature). The command, `readfits`, tells *IDL* to read the `FITS` file into a floating point array called "`image`" and to read the header of the file into a string array called "`header`".

```
IDL> image=readfits('imagename.fits', header)
```

Next you need to display the image. `slide_image` displays the image with a double window, the window on the left shows the full image at low resolution while the image on the right shows the full resolution of the image with scroll bars so you can move around on the image (Figure 46).

```
IDL> slide_image, image
```

Figure 46. Sample of screen display for `slide_image` with default scaling. The left half displays the entire image while the right half zooms in on one part of the image. To move to another part of the zoomed image, use the slider bars on the right and bottom of the window.

You may also want to know what the minimum and maximum values of pixels in the image. For example, you can't see your star in the image that you have displayed, or the star looks odd (as in the example above). If you change the stretch you might be able to see your object more clearly. To do this you can use a few handy functions called `min` and `max` which gets this information out of the image array.

```
IDL> minvalue=min(image)
IDL> maxvalue=max(image)
```

Or you can do this in one step:

```
IDL> minvalue=min(image, max=maxvalue)
```

In this case, `max` is called a keyword for the function "`min`" and allows you to get both values you want with one command. This says, "get the minimum value of the array "`image`" and put that value into a variable called `minvalue`. Also, put the maximum value of the array into a variable called `maxvalue`."

To find out what the value of any array is, type:

```
IDL> print, arrayname
```

For example,

```
IDL> print, minvalue
```

You might also want to know how big your image is and how it is being read (integer, float, string etc) by the computer. You can find this out by typing help and the variable name:

```
IDL> help, arrayname
```

IDL outputs the arrayname, type and value or array size.
For example:

```
IDL> a=[2,3,4,5]
IDL> help, a
A                INT       = Array[4]
```

Once you have determined the parameters of your image as described above, you can display your image with those parameters. For example, you might want to change the display values used by `slide_image` to see a faint source in your image that did not show up with the default scaling. Use the "`bytscl`" function to do this:

```
IDL> image2=bytscl(image, max=maxvalue, min=minvalue)
```

This puts the image into another array so that you can use the original again if you want to play around with different scaling parameters (`max` and `min` are the minimum and maximum of the display that you input as `maxvalue and minvalue`, not by definition the `min` and `max` values themselves). You may find that shrinking the distance between min and max makes a big difference. For the image displayed above, `min=0` and `max=16383`. The display below is scaled from `min=0` to `max=500`. After you have created a new array, display your modified image (Figure 47):

```
IDL> slide_image, image2
```

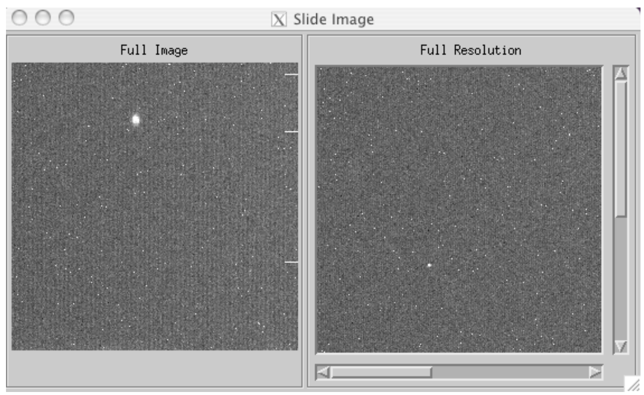


Figure 47. Sample of screen display for `slide_image` with modified scaling.

If you have want to clear a window you can either close the window in the top left corner or use the command "`wdelete`" to delete the last window you displayed.

```
IDL> wdelete
```

Another way to display images is by using a program written in *IDL* called `ATV`. We'll test this with one of the images you have in your Tutorial directory. To open an image using `ATV` type the following:

```
IDL> atv, '/mit/12.410/student/myusername/Tutorial/ps5-07.fits'
```

If this went well, you should now see a window with the image of a single blurry star in it (Figure 48). You can adjust the image (as you were doing by hand before) by using the buttons provided to zoom in and out with your mouse and change the color scaling. If you click on the image and hold your mouse button down while moving the mouse around you can change the contrast of the image. When finished, simply click the `Done` button to get rid of the window.

`ATV` is also useful for determining what `boxsize` you want to use for your data analysis. When you measure the signal or flux in a box around your object, you need to define a box that is large enough to get all your object signal but small enough not to get lots of background noise. `ATV` uses circles instead of boxes (which we use in the class software), but the idea is the same. It is generally found that making the radius of your box about 2-3 times the full-width-at-half-maximum (FWHM) of the stars in the image there is a good balance between object signal and background noise from the sky. In order to determine the FWHM in `ATV` you need to click where it says "`mousemode: color`" and select the "`imexam`" option. Now click on a star in your image. The screen on the right should pop up. If you click on "`show radial profile`" you will get the profile that is displayed below the image statistics. In this window below the image with aperture circles overplotted is a measure of the FWHM. It may be slightly different for different stars on your image, but click on a few stars and determine the mean. Multiply this number by 4 to get the boxsize you should use to input to `phot` in the reduction section of this manual.

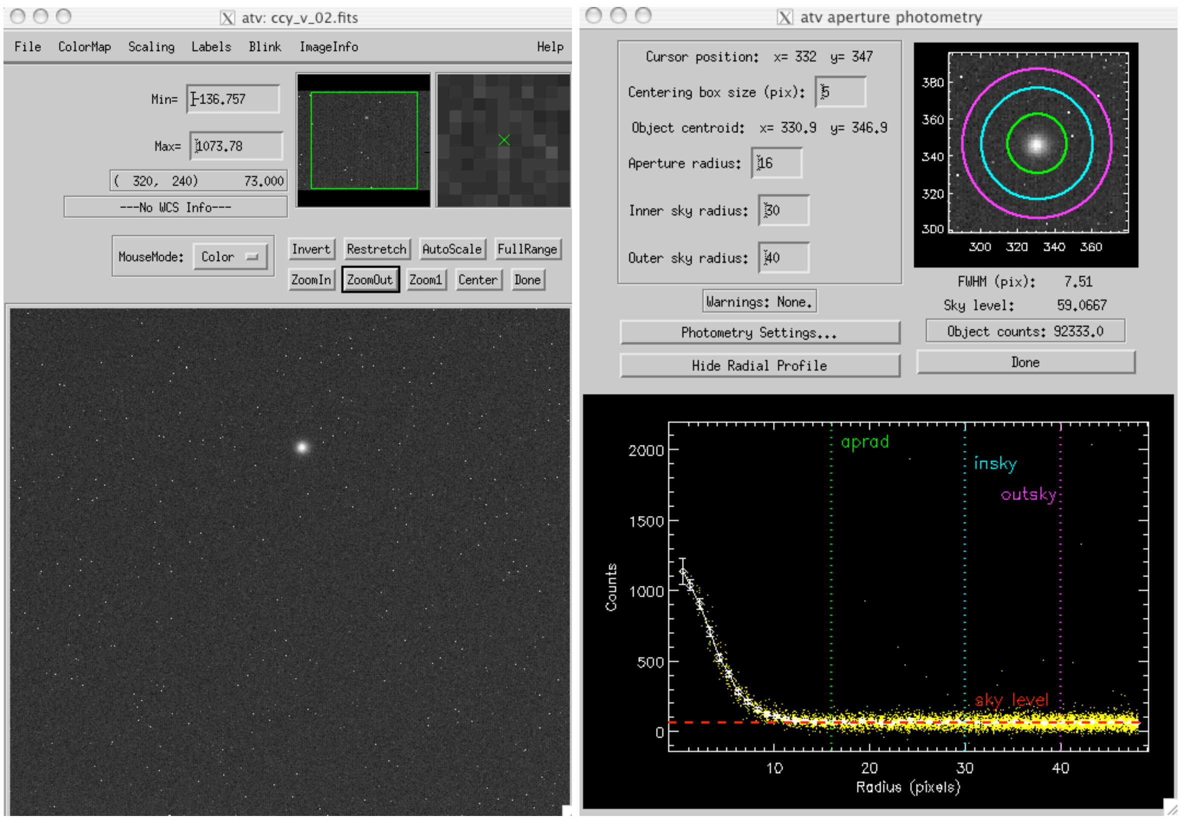


Figure 48. Sample of `ATV` screen display (left) and `ATV aperture photometry` screen display (right). See the text for details about how to use this *IDL* routine.

If you want to learn some simple methods for plotting things in *IDL*, turn to Appendix D. For additional information on other functions in *IDL* you can explore the *IDL* help manual by typing "`?`" at the *IDL* prompt. This will start up the *IDL* help manual in Adobe Acrobat.

5.3.2 *Mathematica*

Mathematica is a powerful application program for doing simple and complex mathematics and plotting your results. It requires a license to run, but is available to MIT students on Athena in the "`math`" locker.

```
athena% add math
athena% mathematica & (for Notebook/X interface)
```

or

```
athena% math (for TTY interface)
```

There are many ways to utilize *Mathematica*. As an end user tool, *Mathematica* can be used to carry out either numeric or symbolic computations. It can be used as a programming tool and has the ability to interface to external programs written in C, Java and other languages. It also has the capability to create graphics (figures, text, equation etc.) that can be exported for use in other documents. In this class, we will not be giving instructions for *Mathematica*, but if you already know it and want to use it for your project that is fine. Some of the teaching staff (Mike Person, and Jim Elliot) use *Mathematica* regularly for their research and can answer questions you might have while doing your project.

5.3.3 MatLab

MatLab (Matrix laboratory) is an interactive software system for numerical computations and graphics. It is especially designed for matrix computations: solving systems of linear equations, computing eigenvalues and eigenvectors, factoring matrices, and so forth. *MatLab*, is designed to solve problems numerically in finite-precision arithmetic. Therefore it produces approximate rather than exact solutions.

MatLab, like *IDL* and *Mathematic,* requires a license to run and is available to MIT students on Athena. It can be found in the "`matlab`" locker.

```
athena% add matlab
athena% matlab -ver number (where number is 5.3.1 or 6.5.1)
```

Again, in this class, we won't give you instruction in *MatLab*, but if you already know it and want to use it for your project it is available to you. If you are trying to fit sinusoids to period data you may find the Junior Physics Lab *MatLab* packages helpful.

`http://web.mit.edu/8.13/www/index.shtml`, and click on "MatLab Curve Fitting" under "Data Analysis".

5.3.4 IRAF

Image Reduction and Analysis Facility, or more commonly, *IRAF* is a general image processing tool. *IRAF* is a product of the National Optical Astronomy Observatories (NOAO) and was developed for the astronomical community. It is often used at telescope facilities for data collection and on the spot analysis as well as more detailed analysis once one has left the telescope. It runs on all platforms and is free for download from NOAO (`http://iraf.noao.edu/`). It requires an X-terminal interface and one of a number of image display programs (*SAOImage*, *DS9*, *Ximtool* etc.).

IRAF has similar packages to the routines you are using in *IDL*; however the user interface does not allow understanding the details of your analyses as easily as the packages we have written in *IDL*.

6 Reducing Your Data

In common language, the terms "data reduction" and "data analysis" are often used synonymously. In this course, however, we shall use "data reduction" to mean a process whereby a large amount of data (numbers) are "reduced" to a much smaller set. An example of data reduction is the extraction of the centers and/or the instrumental magnitudes for the astronomical images on a CCD frame. The centers and magnitudes would typically be a set of a few tens of numbers, while the original CCD frame contains hundreds of thousands of numbers. Further work with the reduced set of numbers is termed "data analysis" and will be described in the next section.

In this course we support a set of data reduction software that runs in the environment described in Section 5.3.1, Interactive Data Language *(IDL)*, which you will access through Athena. The instructions in this section begin with the assumption that you have already transferred your data to your Athena account (as described in Section 4) and that that you have started IDL from your Athena account (as described in Section 5.3.1).

6.1 Calibrating Data

This section describes the steps you need to complete to take your images from being “raw” at the telescope to “calibrated” by subtraction of your bias and dark calibration frames. In *IDL* you can type the name of any calibration routine listed below and *IDL* will print out what the routine expects as inputs. Things in brackets [] are optional inputs.

In all the following routines the “`filelist`” is a list of file names and “`directory`” only needs to be listed if you are not working in the directory where your files are located. To make this filelist or add to an existing list, type in IDL:

```
IDL>$ls filename.fits > output_file_name.lst
```

This is also very useful for putting several files on a list at once. For instance, if you have all of your 30-second light exposures in one directory for a given observation, and wish to compile them on one filelist before analysis, you may go to that directory and type:

```
IDL>$ls Light*30S0*.fits > filelist.sample.lst
```

where a * represents a wild card character, such that all files containing “Light” and “30S0” will be included. The filelist filelist.sample.lst will now be saved in that directory. To view it, you may type:

```
IDL>$more filelist.sample.lst
```

```
———filelist.sample.lst———

Light_NXXX_B1+0C_30S0-1.fits
Light_NXXX_B1+0C_30S0-2.fits
Light_NXXX_B1+0C_30S0-3.fits
Light_NXXX_B1+0C_30S0-4.fits
```

You should make filelists for light, dark and bias exposures and may need to separate them by exposure time and/or filter used. In this way, you may call upon each filelist in the following routines.

(1) Create master bias frame: `makebias`

Purpose: This function takes a list of bias images and averages them to make one master bias image to be used in reducing all of the data for one night.

Calling Example:

```
makebias, '/directory/samplebias.lst', 'masterbias.fits',
[binfac=binfac]
```

Definitions of Input Parameters:

`filelist – ('/directory/samplebias.lst')` This should be a string pointing to a textfile that lists all of the files that you wish to use in creating the average bias image. It can include the path to the images if you want to work in a directory other than the one in which your images are located.

`outfile – ('masterbias.fits')` This should be a string containing the file name (with directory) where you want the master bias image to be stored.

`binfac – (OPTIONAL)` This should be the number of pixels you want to sum in both the x and y directions on your image. For example if you wanted to bin your image 2x2 you would specify `binfac=2.`

Notes: This function doesn't actually display any frames to the screen during its processing or even after the final image is created. Make sure that your final image is what you expect by checking your image using either `slide_image` or `ATV` as described above in the *IDL* introduction.

(2) Create master dark frame: `makedark`

Purpose: This function takes a list of darks images and averages them to make one master dark image to be used in reducing all of the data for one night for one exposure time.

Calling Example:

```
makedark, '/directory/sampledark.lst', 'masterbias.fits',
'masterdark30s.fits', [binfac=binfac]
```

Definitions of Input Parameters:

`filelist – ('/directory/sampledark.lst')`This should be a string pointing to a textfile that lists all of the files that you wish to use in creating the average dark image. Make sure that all these images have the same exposure time. It can include the path to the images if you want to work in a directory other than the one in which your images are located.

`biasfile – ('masterbias.fits')` This should be a string containing the full pathname of the master bias file for use in processing. The master bias file should be created with `makebias.`

`outfile – ('masterdark30s.fits')` This should be a string containing the file name (with directory) where you want the master dark image to be stored.

`binfac` – (`OPTIONAL`) This should be the number of pixels you want to sum in both the x and y directions on your image. For example if you wanted to bin your image 2x2 you would specify `binfac=2`.

Notes: This function doesn't actually display any frames to the screen during its processing or even after the final image is created. Make sure that your final image is what you expect by checking your image using either `slide_image` or `ATV` as described above in the *IDL* introduction.

(3) Calibrate data with bias and dark frames: `multiccdproc`

Purpose: This function takes a list of CCD images (all the same exposure time from one night) and your master bias and dark files (of the appropriate exposure time), and does all of the bias and dark subtraction.

Calling Example:

```
multiccdproc, '/directory/calib30s.lst', 'masterbias.fits',
'masterdark30s.fits', [binfac=binfac, darkscale=darkscale]
```

Your input list should have all your images with a given exposure time to match your input master dark. For example, if you have 30 and 60 second exposures you should have two lists, one for your 30 second images and one for your 60 second images to match your master darks files: masterdark30.fits and masterdark60.fits.

Definitions of Input Parameters:

`filelist` - (`'/directory/calib30s.lst'`) This should be a string pointing to a textfile that lists all of the files that you wish to calibrate. Make sure that all these images have the same exposure time. It can include the path to the images if you want to work in a directory other than the one in which your images are located.

`biasfile` – (`'masterbias.fits'`) This should be a string containing the full pathname of the master bias file for use in processing. The master bias file should be created with `makebias`.

`darkfile` – (`'masterdark30s.fits'`) This should be a string containing the full pathname of the master dark file (for the exposure time corresponding to your images) for use in processing. The master dark file should be created with `makedark`.

`binfac` – (`OPTIONAL`) This should be the number of pixels you want to sum in both the x and y directions on your image. For example if you wanted to bin your image 2x2 you would specify `binfac=2`.

`darkscale` – (`OPTIONAL`) If you forgot to take a dark for some exposure time, this option allows you to scale whatever dark you took to the right exposure time for calibration of your science images. For example if you forgot to take 60 second darks, but took 30 second darks you would specify `darkscale=2`.

Notes: This function doesn't actually display any frames to the screen during its processing or even after the final images are created. You can check your final images using either `slide_image` or `ATV` as described above in the *IDL* introduction.

6.2 Getting numbers out of the images

Astrometry and Photometry Routine: `phot`

Purpose: This function takes a list of CCD images, an output filename and a boxsize. It displays the image then asks you to click on an object of interest followed by a location for measuring the background sky (Figure 49). The function does simple box photometry (it adds up all the counts in the pixels of your box) at both of the locations you defined based on your input boxsize and writes the results out to a text file, your output filename. It allows you to measure one star on the frame or multiple. Each successive star is given a serial number from 0-N. The (x,y) position of your mouse click, the (x,y) position of the object centroid (center of mass of the light) and the center (x,y) position of your background is recorded to the output file as well. This program also has an option to allow you to choose your sky background to be determined from a box around your object instead of from a separately defined region. If you desire to use the function in this way, then use the `/oneclick` flag when calling the routine. If you are measuring multiple objects in a field you may also choose to use the same background for measurement, for this use the `/singleback` flag. If you want to be able to make measurements at specific pixels (useful for projects of fuzzy rather than point sources) then use the `/roam` flag. This will print out the pixel coordinates to the terminal window.

Calling Example:

```
phot, '/directory/path/infilelist.txt', '/directory/path/outfile',
boxsize,  [min=min, max=max, /roam, /singleback]
```

If using oneclick, calling example:

```
phot, '/directory/path/infilelist.txt', '/directory/path/outfile',
boxsize, innersky, outersky, /oneclick, [min=min, max=max, /roam]
```

Definitions of Input Parameters:

`filelist – ('/directory/path/infilelist.txt')` This is be a string pointing to a textfile that lists all of the files that you wish to analyze.

`outfile – ('/directory/path/outfile')` This should be a string containing the full pathname to a text file where you want the photometry and position results to be stored. If the file does not exist a new file will be created, if it does exist the file will be appended to. The file has a header, but for additional reference the columns are recorded as follows and a sample output is recorded below:

> *Independent Box background*
>
> File, Serial, Mouse:ObjectX, ObjectY, Centroid:ObjectX, ObjectY, BackgroundX, BackgroundY, Boxside, Background, Object, Object-Background, StdDevPerPixel, ExpTime, FrameTime
>
> *Box around Object background*
>
> File, Serial, Mouse:ObjectX, ObjectY, Centroid:ObjectX, ObjectY, InnerSky, OuterSky, Boxside, Background, Object, Object-Background, StdDevPerPixel, ExpTime, FrameTime

`boxsize` - This is the number of pixels on the side of a box that contains the area on the image that you are summing. It should be an even number; if an odd number is entered, it is set to the next even number. Your mouse clicks should not be closer than `boxsize`/2 to the image edge. See the discussion on `ATV` to learn about how to determine what your `boxsize` should be.

Options:
`innersky` – This should be an even number, larger than your `boxsize`. It records the inner edge of the box for determining background.
`outersky` – This should be an even number, larger than your `innersky`. It records the outer edge of the box for determining background. Remember you want the area of your sky to be as large as if not larger than your object box.
`min, max` – display parameters in case the auto scale does not seem to work .
`/roam` - if you want to see the pixel readout before you click on the image, add this flag to your command line, it will print out your pixel location of your cursor in the xterm.
`/singleback` - subtract the same background from multiple sources on an image.

Sample output file information:

```
version: 05.06.09
File, Serial, Mouse:ObjectX, ObjectY, Centroid:ObjectX, ObjectY, BackgroundX, BackgroundY,
Boxside, Background, Object, Background-Object, StdDevPerPixel, ExpTime, Date, Time
juno_40_p1_1.fits   000   258.000   225.000   257.854   224.907   314.000   257.000
      6   9692.20   365565.22   355873.03     105.02     40.00   2003-10-20   23.562
juno_40_p1_1.fits   001   271.000   295.000   270.857   294.511   315.000   256.000
      6   9887.60    57781.80    47894.20     103.25     40.00   2003-10-20   23.562
juno_40_p2_1.fits   000   258.000   224.000   257.925   224.164   314.000   257.000
      6   4520.20   357672.50   353152.31     100.53     40.00   2003-10-20   23.586
juno_40_p2_1.fits   001   270.000   293.000   269.998   293.116   316.000   258.000
      6   4433.20    51080.80    46647.60     110.53     40.00   2003-10-20   23.586
```

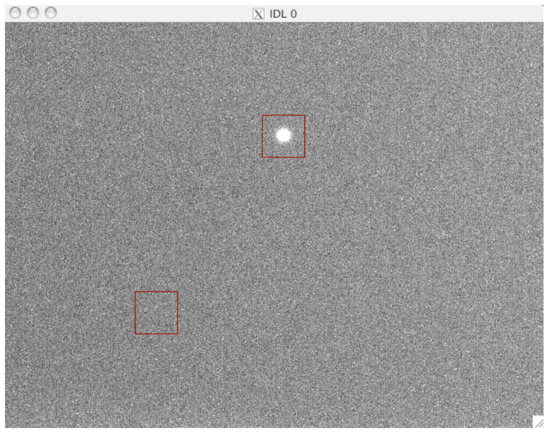


Figure 49. Sample of `phot` display screen with aperture boxes overlaid. See text for program input parameters and outputs.

Spectroscopy: `specextract`

Purpose: This function takes a single CCD image, and an output filename (Figure 50). It asks you to click on a spectrum on the screen, and then click on a background area (near the bottom of the image). It then extracts the spectrum, subtracts the background and writes column numbers and flux values to the output file. It puts the output values in a two column text format that can be loaded into most standard plotting programs for graphing (*Excel, Xess, IDL, Mathematica, Matlab*, etc.).

Calling Example:

```
specextract, '/directory/path/file.fits',
'/directory/path/outfiledata.spec'
```

Definitions of Input Parameters:

`infile – ('/directory/path/file.fits')` Name of the image you want to extract your spectra from.

`outfile – ('/directory/path/outfiledata.spec')` This should be a string containing the full pathname to a text file where you want the spectrum stored. The format of the output is a two-column list: pixel, counts.

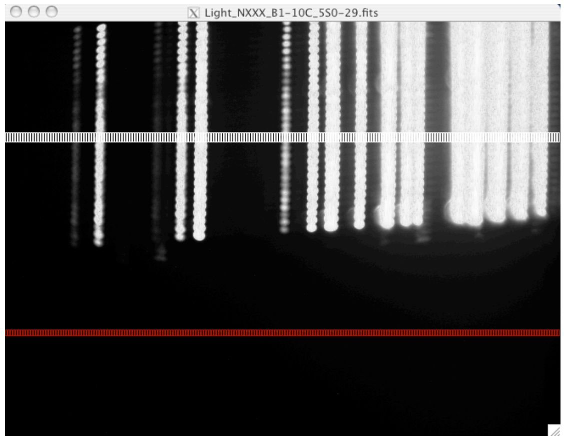


Figure 50. Sample of `specextract` display screen with spectra extraction regions overlaid. See text for program input parameters and outputs.

`specextract_mod`

Purpose: This function takes a single CCD image, and an output filename (Figure 51). It asks you to click on the top and bottom of your spectral area and sums in columns between the values you define. It does not subtract any background, but seems to give better results on faint objects. Using this function you are effectively averaging the spectra from multiple fibers resulting from `specextract`. It extracts the spectrum and writes column numbers and flux values to the output file in a two column text format that can be loaded into most standard plotting programs for graphing (*Excel, Xess, IDL, Mathematica, Matlab*, etc.).

Calling Example:

```
specextract_mod, '/directory/path/file.fits',
'/directory/path/outfiledata.spec'
```

Definitions of Input Parameters:

`infile – ('/directory/path/file.fits')` Name of the image you want to extract your spectra from.

`outfile – ('/directory/path/outfiledata.spec')` This should be a string containing the full pathname to a text file where you want the spectrum stored. The format of the output is a two-column list: pixel, counts.

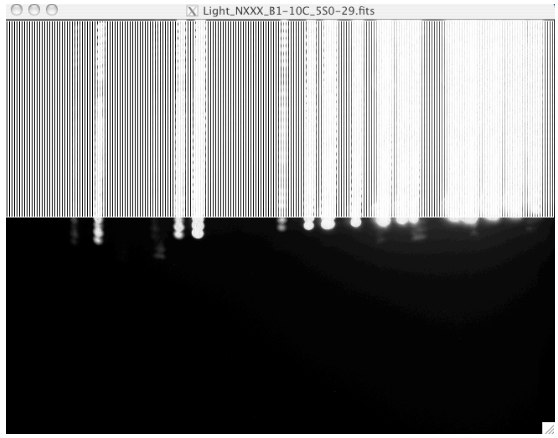


Figure 51. Sample of `specextract_mod` display screen with spectra extraction regions overlaid. See text for program input parameters and outputs.

7 Analyzing Your Data

You may choose to work in one of the environments already discussed (*IDL*, *Mathematica*, *MatLab*, etc.), or if you are not familiar with any particular software, we recommend that you use a spreadsheet program (e.g. *Xess* on Athena, or *Excel* on Windows or Mac).

Astrometry

1. Select the standard star (centroid) x,y coordinates out of the file you created with `phot`.
2. Use the ra, dec coordinates for these stars to calculate the plate scale and rotation angle for each of your frames.
3. Use the plate scale and rotation angle from step 2 to solve for the ra and dec of your object.
4. Complete any farther analysis such as calculation of an orbit.

Photometry

1. Using the output of `phot`, calculate magnitudes for each of your measurements (for your object and standard stars)
2. Create an airmass-extinction plot with your standard stars.
3. Use the results from your airmass-extinction plot to calculate calibrated magnitudes for your object(s) of interest.
4. Plot your results (magnitude vs. time, B-V etc.)
5. Fit models to your results, calculate relevant quantities, etc.

Spectroscopy

1. Determine your wavelength calibration with the argon spectrum. Plot flux vs. pixel and use the CRC to determine which lines match which wavelengths.
2. Plot wavelength vs. pixel and fit the result with a line to get your transformation relation.
3. Apply your transformation relation to the pixels in your spectrum of interest.
4. Plot your results as wavelength vs. flux.
5. Interpret your results.

Appendix A: Choosing and Planning a Project

The first step in carrying out your class project is to decide on what your project will be. Your course project should answer a scientific question with a set of astronomical data that you acquire with a telescope. After choosing a project, you need to flesh out the basic idea with more details of exactly what data you need, how you will calibrate the data, how you will reduce the data, and what analyses you plan to carry out in order to answer your scientific question. This information should be given in your project plan, which is a written document that you will also present orally, as part of the communications component of the course.

Choosing a project

Your choice of a project will be constrained by several factors: (i) requirements of the course, (ii) your own criteria, and (iii) constraints imposed by limitations of the observability of astronomical objects (only half of the sky can be above the horizon at any given time; trees or lights may block your horizon, etc.) and the equipment. These are discussed in the following sections.

Project criteria imposed by the course

The criteria for an acceptable project are simply that your project should answer a scientific question with a set of astronomical data that should take no longer than 3-5 hours to acquire under clear skies with available facilities. The results of your analyses should be quantitative and include a rigorous error analysis.

Project constraints imposed by observability and the available equipment

Will the object(s) that you want to observe for your project be well above the horizon (as viewed from Wallace Observatory) in the first part of the night during September and October? Remember that there are trees at Wallace Observatory so the object must be above 20° for at least three hours on any given night. Are the objects bright enough to give a strong signal with the available telescopes and instruments? Check the magnitude(s) of the object(s) of interest and compare with the limiting magnitude of the telescope you will be using. If the answer to either or both of these questions is "no," you may be able to find other objects of the same type that are brighter and/or better placed for observation. Consult your lab instructor for help with these issues.

Your criteria for a project

Be sure to pick a project that you find interesting—either because of the type of object or the technique that would be used. We expect you to get help from your lab instructor to pick out a good project. By “good” we mean a project for which it is possible to collect the necessary data within 3-5 hours and analyze the data to achieve your desired result. We want you to be successful with your project, and we will tell you if we think a particular project would be too difficult. However, if we think you have a good basic idea, we may help you modify your project so that it can be successful within the scope of this course.

You can ask yourself two questions:

1. **Type of object to look at:** Do you want to look at solar system objects, at stars or, at fuzzy things (like galaxies and nebula).
2. **Type of measurement:** Do you have a preference for *astrometry* (position measurements of objects), *photometry* (brightness of objects), or *spectroscopy* (brightness of objects vs wavelength).

Some combinations of objects and measurements make more sense than others, but responding to these two questions will at least get you pointed in the right direction and give your lab instructors some ideas about where to direct you in choosing a project. Unfortunately, some of the projects that you would find most interesting will not be possible because they would require a larger telescope, better site, or an instrument that we do not have. For example, measuring the redshift of a galaxy with the equipment available to you would be extremely difficult (if not impossible). However, if you are interested in galaxies, instead of trying to measure red shifts you could measure the colors of one or more galaxies and use these data to infer the relative numbers of different types of stars that comprise the galaxy.

Some suggestions for projects

Below we discuss some ideas for projects, which we have grouped according to the type of measurements that you would make. Certainly there are more potential projects in each group than appear below. You can get more information about potential projects through discussions with the teaching staff and your own investigations of reference materials (library, world-wide web, and the course hand outs). For a list of useful resources, please see Appendix C. We expect you to flesh out the details, but keep asking us questions; after all, we love astronomical observations!

Ideas for astrometric projects

Astrometric projects generally involve moving objects. Although all celestial objects move relative to each other, only those within our solar system will have enough angular motion to be detectable during the term. So an astrometric project could be to determine an orbit of an object—either the orbit of a satellite around a planet or the orbit of an asteroid (*a.k.a.* minor planet) around the sun. Since the instantaneous orbit of a body lies in a plane and a plane can be determined from three points (not collinear) you would need observations at three different times to establish an orbit. To get good leverage on establishing the orbit plane, however, your measurements should be spaced in time over the orbit. Satellite periods are of the order of days, so you can sample an entire orbit during the period of observations for this class. Asteroids, on the other hand, have orbital periods of years. Over a few weeks you could get a first order solution for an orbit, or you could improve the accuracy of an existing orbit by combining your new data with older data.

On any given night you want to take a series of measurements on your object (about ten frames each time) and then come back another night (your next lab section, or next few lab sections, for example) to get more measurements of the position of your object. You could do this with any filter but the *R* filter gives the strongest signal for most solar system objects. You need to make sure that in addition to your satellite or asteroid, there are other objects in each CCD frame with a known position that you can use to establish a celestial reference frame.

Ideas for photometric projects

Photometry projects are the most diverse. Some photometry projects measure an object in the same filter vs. time, which you can use to determine the rotation period of an asteroid, or the period of a variable star. Basically you want a certain amount of time on one night to observe your object of interest, taking as many images as you can during this interval.

Another idea for photometric project would be to make a Hertzsprung-Russell diagram for an open cluster, from which you can determine the age of the cluster (see almost any basic astronomy text for more information). For this project you would pick a cluster and measure the magnitudes of several stars in different filters (U, B, V, R, and I are available, but you need only two).

If you are doing photometry of a galaxy or open cluster instead of sitting on one patch of sky for the entire night you might want to move the telescope around to different parts of your object (different parts of your galaxy or different stars in the cluster) throughout the time you are observing. You don't need a comparison star in the field but you do need to take standard star observations as described above so you can get actual magnitudes for the stars you measure. At each position you should take between 3 and 5 exposures in each filter for both your object(s) and your standard stars.

For any photometric project you need to calibrate the magnitudes of your objects. For these you need to measure stars of known magnitudes, called "standard stars." Standard stars should be observed before the first observation of your object and after the last observation of your object. If you are observing with multiple filters you need to make sure you take observations of your standard star in all the same filters as your object. You should take between 3-5 exposures each time to check the consistency of the results. If you are measuring a rotation curve you can use the technique of *differential photometry*, by measuring the light from another star, which we'll call a "comparison star" in the field with your object at all times.

Ideas for spectroscopic projects

Spectroscopy is the characterization of a celestial body's light by wavelength, generally in order to investigate the composition and/or physical processes of an object. For example, you might compare the spectral lines of different types of stars to understand what determines these different types. Or, you could look at the spectral signature of a planet's atmosphere or surface, and compare it to what we know about the Earth. Since a spectrum spreads out the light from an object over many pixels of the CCD, you will need longer exposures with the spectrograph for an object than with direct CCD imaging through a filter. For fainter, extended sources, you may need to take a number of observations and add them together to give a solid result. The spectrograph works in the same basic way as the direct imaging telescopes except instead of centering your object in the field of view you want to properly align your object with the grating.

For spectroscopy, there are two main calibrations that need to be done: wavelength calibration, to determine the wavelength of every pixel, and background subtraction, which accounts for the dark current and CCD bias. It is generally wise to do wavelength calibration before and after your observations to make sure nothing changed in-between. We do this by using an argon lamp for which we know the composition and can match up the wavelengths of argon to our measurements at different pixel positions.

For more information on astrometry, photometry and spectroscopy, see Sect. 3.3 - Astronomical Image Data

Collaborations on projects

Although each student should carry out a project individually, limited collaborations can be of benefit. For example, it two students are interested in making an Hertzspring-Russell diagram of the Pleiades the project could be accomplished individually with the measurement of about 15 stars. However, if the two students each collect 15 stars and share their data it is possible for their final graphs to have 30 points, giving a much stronger result. If you share data you need to acknowledge the person you have collaborated with in your individual paper and you also need to include as much information as you can about your assessment of that data – did you get raw images from your collaborator or data in some stage of reduction (instrumental magnitudes, calibrated magnitudes etc.).

Choosing Specific Object(s) for Your Project

Once you have chosen the type of project you want to do, it is now time to choose a specific object to observe. Here are some questions to answer, along with useful resources to help you find specific targets given the conditions at Wallace. The following is not an exhaustive list, and you should consult your lab instructor for further input and ideas. As discussed above, your object should satisfy three criteria. First, and foremost the object should be suitable for your project goals. For example, if you want to measure an asteroid's light curve, you must pick an asteroid that has a light curve amplitude of no less than about 0.15 mag or so. Also, it must have a short enough period to allow reasonable coverage of most phases of the light curve. Second, your object should be more than 20° above the horizon from early evening for at least several hours. As a useful first tip, it is highly encouraged to choose an object that is rising at the beginning of the night rather than setting, so you are less constrained by time. Finally, your object should be bright enough to give a good signal (brighter than $m \sim$ 10-11).

Choosing an Asteroid

Asteroids are very versatile and popular project objects in this course. Using astrometry, one may measure an asteroid's trajectory around the Sun. Using photometry, one may measure the light curve of an asteroid and obtain its period. Whichever project you may choose, asteroids are generally reliable objects to observe, but require a several nights of observing time to obtain good results. Often, you will need to direct your telescope to the asteroid at the beginning of the night, and take observations periodically throughout the entire observing session. Therefore, you must choose an asteroid that is above the horizon for a significant amount of time on any given night between September and October. You may browse websites for Near Earth Objects, or Main Belt Asteroids. You will need to do some research with Starry Night (Sect. 1.1) to make sure any asteroid you choose is observable for enough time. For more resources, refer to Appendix C: Useful Websites.

Choosing a Solar System Planet or Satellite

Planets and their satellites are reliable objects to observe due to their brightness. However, your choices are limited for the small window of time given. Use Starry Night (see Section 1.1) to help you figure out which ones are up on the nights you want to observe. For planets, check the angular size of the planet and compare that with the CCD's angular dimensions to make sure the planet is small enough, should you want to take exposures.

Choosing a Star

Do some research on the types of stars that would be observable with the telescopes available at Wallace. The following questions may help you get started. What is the magnitude of the star, and will the star be easily detected given the equipment? If so, which filters, if any, should be used? If the star is variable, what is the amplitude and variability of the star – do you think this will be significant enough to detect in a light curve?

Once you have decided on a type of star, you may research (using a combination of books, the Internet, and Starry Night) to figure out which exact star would be most suitable for the course's observing conditions. Generally, variable stars are useful objects to study for photometry because one can easily build a light curve, if the variable star has a small enough period. Dwarf Cepheids are convenient to observe because they have short periods and high amplitudes. Any other type of variable star is good for astrometry or spectroscopy, as long as it has a high enough magnitude. For more information, visit www.aavso.com.

Recording a Transit of an Extrasolar Planet

Extrasolar planets are relatively recent to the astronomical field, and extrasolar planet transits are very intriguing to observe. However, they are tricky and require a very detailed observation plan. Transits occur when a planet passes between its parent star and the observer, partially blocking the light from the star from reaching the observer. The key is to find a few transits that occur in September and October, and to be prepared to observe on all of those nights. A successful observation of a transit only takes one very clear night. However, there may only be a few transits that occur over a two-month span, and only one of those nights may be clear. There are also only a few extrasolar planets that are observable in the Northern Hemisphere. Needless to say, this is an extremely difficult project because the transits have small amplitude (~0.01 mag) and the specific times when transits occur may not be clear. This project should be attempted only by those with experience.

Other Possible Objects of Interest

Planetary Nebulae (spectra); galaxies.

Planning a project and writing your project plan

The main purpose of your project plan is for you to present your understanding of what will be involved in achieving the scientific goal of your project to the teaching staff. Then the responsibility of the teaching staff is to either (i) confirm that your project is feasible within the scope of the course, or (ii) suggest modifications to your original plan that would result in a feasible project. Hence, your project plan is an "interface document" between you and the teaching staff, and as such it should be clearly written. "Clearly written" does not mean that you completely understand all aspects of your project at the beginning. It does mean that the written document explains what you do understand about your project, and it also raises questions about those aspects of the project that may be somewhat unclear to you.

The process of planning your project and the process of producing a written plan to submit to the teaching staff can (and should) be a combined activity. As you learn more about what your chosen project involves, in terms of what data you need and the subsequent data processing, you will be making notes for yourself. These notes can then be grouped together into an outline, and then the outline can be expanded into a written document. The level of detail expected is about what can be written in 3-5 pages (excluding display items, such as tables, figures, and equations).

Your plan should begin with the scientific question that your project will try to answer. This should include a brief description of why the question is of scientific interest to both you and others in astronomy or related fields. This might include a brief discussion of the science behind your project and what your project hopes to add to what is already known. If you expect certain results you should describe those and if there are challenges associate with your project (data collection or analysis) you need to write about this as well.

Following the definition of your project, you will need to address what data will be needed to answer the question. We do not expect the exact details of every exposure that you plan to record, but we do need to know: what instrument you plan to use (*i. e.* a CCD camera with direct imaging or spectrograph), if you need a particular telescope in the shed, what objects you plan to observe (will they be visible from Wallace Observatory this time of year?), and what calibration data (both sky and detector) you will need. The fainter the object, the longer the exposure times need to be to achieve an acceptable result (we will help you to estimate exposure times). The total amount of data for your project should fall in the range of 3-5 hours.

After specifying the data to be recorded, plans for reduction and analysis should be discussed. Much of the reduction software supported by the course is described in this manual—you can assume that the software exists and will function as advertised. Please describe the processes as you understand them in the software, rather than just saying that you will use the class packages to get numbers from your images. We want to know that you understand what the software is doing not what code you are running. Analyses have (purposely) not been described in detail in this manual, so that you can insert your own ideas and skills.

Although we have not given detailed information in this manual, the teaching staff would be pleased to help you develop your own ideas about how you would like to analyze your data, and to discuss the feasibility of what you want to do. Again the details of your plans for data analysis do not have to be known at this point.

Appendix B: Project Plan Guidelines

The purpose of the communication component of 12.410 is to support you in the writing and speaking aspects of being the best scientist you can be.

We want all of your projects to be successful. We also want you to experience the maximum possible learning—in astronomy as well as in proposal and report writing, presentation, and peer review.

The Project Plan Writing Process

What? A 3- to 5-page telescope proposal (excluding Figures and Tables)
A 5-minute oral presentation

When? Consult the course Stellar web site for the due dates of your Project Plan, the revison to your Project Plan, and the oral presentation of your Project Plan.

Why? The process of writing, presenting and revising your project plan serves several purposes:

1. It gives you experience with writing a proposal to request telescope time, which is a kind of document commonly used by astronomers.

2. It helps you determine what you want to accomplish and what questions you need to answer before you begin your project.

3. It gives your teaching staff an opportunity to evaluate whether your project is feasible and, if necessary, to help you modify it.

4. It fosters a professional aspect to your relationships with your peers.

How? Organize your plan in three parts:

Goals and Purpose
Describe in a few paragraphs what you intend to do and how your project might be of use or interest to other astronomers. Pose as clearly as possible the scientific question your project will address. Present any background information that will help you and your readers understand and contextualize your question and results, including the underlying science and anything you hope your project will add to what is known.

If you expect certain results, describe them along with your reasoning for expecting them. If you foresee challenges associated with your data collection or analysis, identify and discuss them as best you can.

You are not expected to have all the answers, or even to predict all the relevant questions. The more you can identify unknowns or potential problems, though, the better the staff can help you design and plan a successful project.

Observation Plan

List the object(s) you will observe, their locations and time in the sky, the equipment you will need, and approximately how much time you will need with that equipment (assuming no major problems arise).

You should require in the range of 3 to 5 hours of telescope time to complete the data collection for your project.

Part of the purpose of this section is to aid your planning. Another part is to aid in the scheduling of equipment. So please include as much information as you can about what instrument(s) you will need, whether you need a particular telescope in the shed, what objects you plan to observe, and what calibration data (both sky and detector) you will need.

Your requests will be coordinated with all of the other projects on both teams.

Analysis Plan

Discuss your plan for reducing, presenting and analyzing your data.

The focus should be on what point you expect to make and what conclusions you will generate, including but going beyond identifying the software packages you expect to use. You will want to describe how you will use a given software package, what results you expect, and how those results relate to your research question. Elaborate detail is not required.

If you have any questions about how to do the science or the writing, please ask your staff.

Appendix C: Oral Presentation Guidelines

The purpose of presenting your Project Plan to the class is to give you practice in communicating your work effectively and professionally, and in fielding questions to get the maximum value from your staff and peers.

Whatever your future holds, a significant component of it will almost certainly be presentations of your work. Many people do not particularly like giving presentations, but almost everyone can become proficient, reasonably confident, and effective.

In conjunction with your written work, we will learn about how to produce and use effective visual material.

In addition, we will work on the art of eliciting helpful questions from your audience, and answering them with poise. When you are effective with Q&A, your presentations become opportunities not just to deliver your work, but also to learn, explore and expand your understanding.

What? A 5- to 6-minute presentation of your Project Plan
Approximately 5 slides derived from your Plan
Approximately 2 minutes of Q&A

When? Check the Stellar web site for the date of your oral presentations.

Why? Presenting your project plan serves several purposes:

1. It helps you focus your thinking.

2. It provides immediate feedback on your preparation.

3. It gives you an opportunity to consider others' questions, thoughts, and ideas about your Plan, and to explore things you may have missed.

4. It helps you build confidence, both about your work and about your ability to express it professionally.

How? Further details about the content and delivery of your presentation are posted online. The essential points:

Prepare to be brief
Five minutes is not long. You will not cover everything. Select wisely.

Craft your visuals carefully
As a rule of thumb, use one slide for each minute of speaking. Make sure your slides are easy to read. Select slides that focus on essential points.

Practice out loud, repeatedly, and in front of a mirror
You talk to yourself at a different rate than you talk in front of a room. Practice out loud. If possible, record or observe yourself.

Pay attention to, and address, your audience
Do they understand you? Are they interested? Are they pondering? Work with them. Talk to them. Put yourself in their shoes.

Prepare for questions
Questions can illuminate strengths and weaknesses of your Plan, and help you develop your work. The way in which you elicit and respond to questions can have an effect on the quality of questions you elicit.

If you have any questions about your oral presentations, please ask your staff.

Appendix D: Project Report Guidelines

This document describes what we are expecting in your project report. Simply stated, your report should describe to a knowledgeable person (*e.g.* your lab instructor, lecturer, or fellow student):

(i) what you set out to do and perhaps something about why;
(ii) what you did (procedure, data, reduction & analysis methods, results); and
(iii) what you learned (conclusions).

There is no set requirement as to length; write as much as you need to in order that your audience have a clear understanding of your project. The written portion, if concise, could be as short as 10 to15 double-spaced pages, plus tables and figures. Clarity and coherence are more important than page numbers.

A good Project Report has many variables. The <u>Mayfield Handbook of Scientific and Technical Writing</u>, written for use at MIT, offers clear and succinct advice and requirements. (http://web.mit.edu/writing/temp2/home.htm).

Detailed information about the content, structure, and style of your Project Report will be posted. Some essentials follow.

Organization

Below is one example of a typical organization for a Project Report.

ABSTRACT: a concise statement of the project (half a page or so, single-spaced), including the most significant results and conclusions. A reader should be able to determine from the abstract whether to read the entire report. It answers questions such as, "What is this about?" or "What makes it important or interesting?" or "How does this research fit the current state of knowledge?"

INTRODUCTION: a summary of how you began the project. A good introduction addresses issues such as what question(s) you set out to answer, what motivated you to do the project, what approaches you considered, and your reasoning for the approach you ultimately chose. It includes enough background information so that your audience (your peers and teaching staff) can follow your work without undue effort. The introduction is often written after the rest of the report, and is a particularly good section to ask others to comment on.

OBSERVATION: a description of what you did, providing enough detail so that someone reading it could reproduce your work. This section generally includes, but is not limited to, detail about the specific equipment you used and why. It may also include difficulties you encountered and how or whether you overcame them.

Your observation section will probably include a table summarizing your observations, and may include a figure illuminating the thinking behind your method.

DATA REDUCTION: an explanation of how you went about analyzing your data. What software did you use? What equations did you use? What intermediate results did you arrive at?

RESULTS: a description of the results you did, and did not, achieve. Were your expectations met? Did you have any surprises? Did you reject any data? Did you confirm anything, or did your data suggest any rethinking of prior work?

CONCLUSIONS: a summary of what your report suggests or reveals. What did you learn? How was your initial, introductory question answered (or not)? What other questions arose? What might you have done differently? What questions are left outstanding? What next questions are suggested by your results?

Figures, Tables, and Equations

One essential component of your Project Report will be the figures, tables, and equations that illustrate your work. A reader should be able to grasp the essential points of your report just by studying your visuals and reading the captions.

Selecting or creating the best ways to visualize information is a complex task. You will probably learn a lot from studying others' examples. Another good way to learn about the visual display of information is to show your draft figures and tables to others for comment.

Label and caption your visual elements clearly and informatively. Each caption should thoroughly summarize the contents and implications of the figure.

Give only the essential equations. Spell out the variables in your text, before inserting the entire equation, so that your reader understands it easily.

References and Citation Protocol

The citations in your report are expected to conform to professional standards. This means that all the material used in your report should be properly cited, with two exceptions: that which is your own creation, and that which is common knowledge.

Before you begin writing, read and thoroughly understand MIT's Handbook of Academic Integrity (web.mit.edu/due/handbook.pdf). This document makes abundantly clear when and how to use citations. Make sure you understand plagiarism in depth, including the proper use of paraphrasing.

In professional writing, citations serve several purposes. They allow your reader to pursue some aspect of your work in more depth by delving into the sources that you have drawn on. In addition, they give credit to others for the work upon which you are building, just as you would expect your work to be credited by others.

For this paper, use the citation style found in *Icarus*. (Note that preferred citation style varies among disciplines and even between journals.)

When referencing another's work within your report, place the citation at the end of the relevant passage, in author-year format, *e.g.,* (Smith 1998), or (Clark *et al*. 2000).

Each author-year citation within your report should correspond to a full reference in a References section at the end of your report. A bibliography containing the references you used is not a substitute for proper citations.

Appendix E: Telescope Specifications

Information about the telescopes and available instruments at the George R. Wallace Astrophysical Observatory can be found at the universal record locator (URL) `http://web.mit.edu/wallace/ShedIndex.html`.

Appendix F: Useful Websites

Class web page: http://stellar.mit.edu/S/course/12/fa07/12.410j/index.html
Wallace Astrophysical Observatory: http://web.mit.edu/wallace/

<u>**Finder Charts**</u>
VizieR Service: http://vizier.u-strasbg.fr/viz-bin/VizieR
Digitalized Sky Survey: http://archive.stsci.edu/cgi-bin/dss_form
USNO Image and Catalog Archive: http://www.nofs.navy.mil/data/FchPix/
Skyview: http://skyview.gsfc.nasa.gov/cgi-bin/skyadvanced.pl

<u>**Asteroid Information**</u>
Asteroid Services: http://asteroid.lowell.edu
JPL Horizons (Ephemeris service for minor planets): http://ssd.jpl.nasa.gov/cgi-bin/eph
Koronis Family Asteroid Project: http://www.koronisfamily.com
Minor Planet Center: http://cfa-www.harvard.edu/iau/mpc.html

<u>**Star Information**</u>
Data Access: http://www-gsss.stsci.edu/support/data_access.htm
Standard Stars: http://plato.phy.ohiou.edu/~tss/ASTR410/standards.html

<u>**Astronomy Reference**</u>
Astronomy Articles: http://adsabs.harvard.edu/abstract_service.html
Students for the Exploration and Development of Space (SEDS):
http://www.mit.edu/~mitseds/resources.html
Space Science Missions: http://spacescience.nasa.gov/missions/index.htm
Heaven's Above: http://www.heavens-above.com/

<u>**Spectroscopy**</u>
Calibration: http://www.physics.arizona.edu/~haar/ADV_LAB/spec2.txt
Introduction: *Getting the Most from a CCD Spectrograph* by Sheila Kannappan and Daniel Fabricant. <u>Sky & Telescope</u>. July 2000. p. 125-132.

<u>**Boston Weather Information**</u>
Satellite Information: http://www.rap.ucar.edu/weather/satellite/
Clear Sky Clock: http://web.mit.edu/wallace/CSC.html
National Weather Service:
http://www.srh.noaa.gov/data/forecasts/MAZ005.php?warncounty=MAC019&city=Westford

<u>**Software Tutorials**</u>
IDL: http://www.ugastro.berkeley.edu/tutorials/tutorials.html
Mathematica: http://library.wolfram.com/conferences/devconf99/withoff/index2.html
http://web.mit.edu/acs/www/numerical.html
MatLab: http://web.mit.edu/afs/athena/software/matlab/www/home.html

IRAF: http://aci50.astronomy.pomona.edu/common/webdocuments/iraf/beg/beg-intro.html

Astrometry

Introduction: http://cfa-www.harvard.edu/iau/ps/info/Astrometry.html

Photometry

Of Asteroids: http://www.minorplanetobserver.com/astlc/PhotometryGuide.htm

Updated: 2004-09-07

Appendix G: Plotting with *IDL*

Reading a file with columns of data

There are a few ways to read a text file with *IDL*. The simplest method is described below, other ways can be looked up in the *IDL* help. This method assumes the file is column delimited. There is a handy function in *IDL* called `readcol` which will read information from a textfile based on a few simple inputs. `readcol` assumes all the values in your file are floating point unless you tell it otherwise.

If you want to read a string you need to define the array first:

```
IDL> array1=''
```

To read a file then type:

```
IDL> readcol, 'filename', array1, array2, array3, format='(a,f,f)'
```

This tells *IDL* to open the file called filename and to read all the lines that have three columns: the first column is defined to be a string and the second and third columns are floating point numbers. If you want to skip a column in your file you can put an "x" in the format statement, `format='(a,f,x,f)'`.

Plotting arrays

Once you have information from your text file in arrays you will likely want to plot your results. For example, you can read in a file that looks like:

———————juno_photometry.txt——————

File, Serial, Background, Object, Object-Background, StdDevPerPixel, ExpTime, FrameTime

juno_40_p1_1.fits	000	9692.20	365565.22	355873.03	3780.72	40.00	23.5622
juno_40_p2_1.fits	000	4520.20	357672.50	353152.31	3619.08	40.00	23.5858
juno_40_p3_1.fits	000	5075.20	354466.81	349391.62	22241.9	40.00	23.6281

————————————————————

then plot your object-background signal vs. time (Figure 52). To do this execute the following set of commands:

```
IDL> readcol, 'juno_photometry.txt', imagename,serial,back, object,
object_back, error,exptime,frametime, format='(a,a,f,f,f,f,f,a)',
delimiter=','

IDL> plot, frametime, object_back, psym=4, xtitle='time (hours)',
ytitle='flux (object-background)', title='Juno lightcurve'
```

`plot` takes two arrays for x and y.

`psym` defines the type of point you want plotted (if you want it to plot a line you can use `linestyle` instead of `psym` where different numbers are used for different types of lines, dashed, dotted etc.), in this case diamonds.

`xtitle` is the label for the x-axis

`ytitle` is the label for the y-axis

`title` is the title of the plot.

There is a lot more power to this command, but that is left for you to explore on your own.

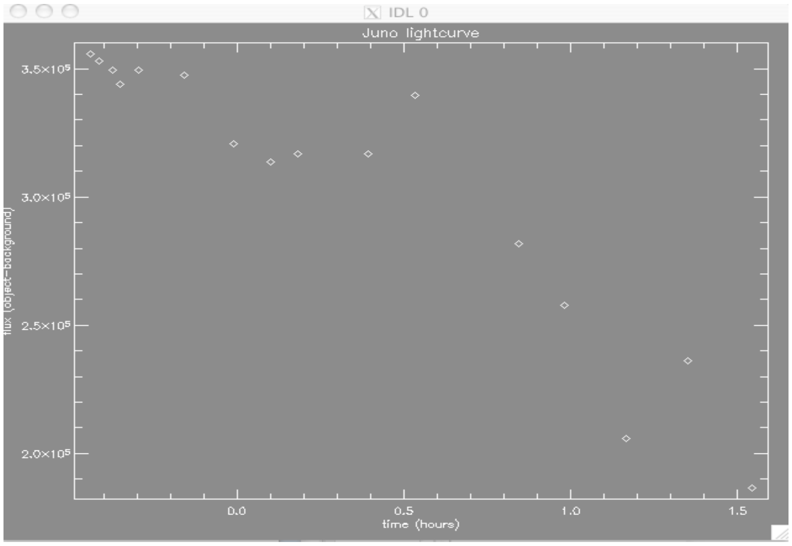


Figure 52. Sample of screen plot in *IDL*. Notice that the plot has a title and both axes are labeled.

Lastly, you might want to plot error bars on your measurements (Figure 53). The command for that is similar to `plot`:

```
IDL> ploterror, frametime, object_back, error, psym=4, xtitle='time
(hours)', ytitle='flux (object-background)', title='Juno lightcurve'
```

Here we've added one more array, "`error`", before defining the point style for plotting. NOTE: remember that the "error" in the output file is per pixel so you need to multiply by the boxsize for the values to be correct.

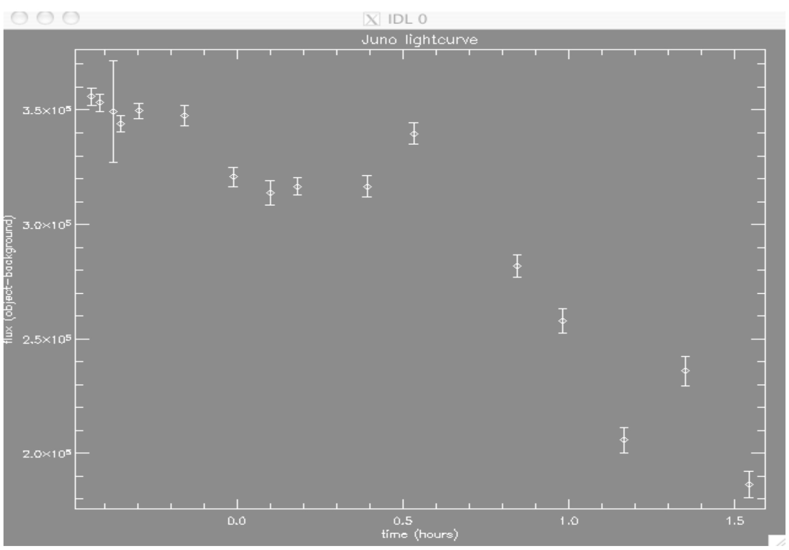


Figure 53. Sample of screen plot with error bars in *IDL*. Notice that the plot has a title and both axes are labeled.

Creating a Postscript file of your plot

You may want a hardcopy of your plot. To do this you need to tell *IDL* to output to a postscript file rather than to the display. To do this you use the *IDL* command `set_plot`.

```
IDL> set_plot, 'ps'
```

Now, rerun your plot command:

```
IDL> ploterror, frametime, object_back, error, psym=4, xtitle='time
(hours)', ytitle='flux (object-background)', title='Juno lightcurve'
```

You can make as many plots as you like. Each plot will print to a different page in the default output file "`idl.ps`".
If you want to see your results on the screen again you need to reset the plot to the display:

```
IDL> set_plot, 'X'
```

You can switch between these two displays as many times as you like. Once you are finished printing things to the postscript file, however, you need to close the file. To do this you need to exit *IDL*.

```
IDL> exit
```

You should now see a file in your current directory called `idl.ps`. This is the output of your plot(s). You can now print your plots to the default printer by typing:

```
athena% lpr idl.ps
```

At this point you should also rename your file to something more useful. If you leave it as `idl.ps` it will get overwritten the next time you plot from *IDL*. For the sample data in this section you might want to name your file "`juno_lightcurve.ps`". You can do this by typing:

```
athena% mv idl.ps juno_lightcurve.ps
```

Once you have created a postscript file, if you would like to look at it on the screen before printing, use *ghostview* on Athena, Figure 54:

```
athena% gv juno_lightcurve.ps
```

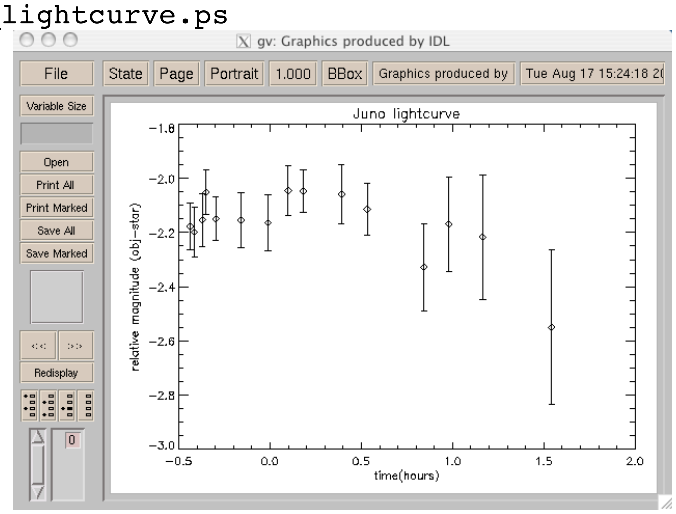


Figure 54. Sample of *ghostview* display of postscript file. With this program you can check that you printed what you expected to your file and also print your figures to hardcopy.

Creating a .tiff image from your .fits file

fits2tiff, fits2tiffr

Purpose: This function takes a single CCD .fits image and converts the file to a .tiff image so that you can put it in a word document or print it as a pretty picture. There are two versions, the first (fits2tiff) assumes you want the same size output file in both dimensions, the second (fits2tiffr) assumes you want different dimensions in x and y.

Calling Example:

```
fits2tiff, file, outsize, centerx, centery, min, max
fits2tiffr, file, xsize, ysize,centerx, centery, min, max
```

Definitions of Input Parameters:

`file` – `('/directory/path/file.fits')` Name of the image you want to convert
`outsize` – boxsize for your output file around a center coordinate.
`xsize, ysize` – dimensions in each direction, x and y, respectively for the output image
`centerx` – center "x" coordinate of extracted image.
`centery` – center "y" coordinate of extracted image.
`min, max` – limits on stretch of image

Calculating instrumental magnitude and errors from PHOT file

This section describes how to go from the output file created by the *phot* IDL routine to instrumental magnitude measurements with error bars.

Before beginning, let us define some terms. The output of *phot* contains several columns of data, the four most relevant for our discussion being *Background*, or the sum of the pixel values in the background frame, which we call **B** here; *Object*, or the sum of the pixel values in the foreground frame, which we call **F** here; *Object-Background* or **F-B**, which we call **S** here; and S*tdDevPerPixel*, which we call σ_p here. We define N_B to be the number of pixels in the background frame, and N_F to be the number of pixels in the foreground frame. For this class, $N_B = N_F$, typically. We let Δt be the integration time of a single image, and m_I be our label for instrumental magnitude. Finally, the error in a quantity x will be labeled as Δx.

Error in the signal: The variance of **S**, the signal, is due to two independent sources: random background noise, and photon counting noise. Since **S=F-B**, the variance due to random background noise is $\sigma_F^2 + \sigma_B^2$. The photon counting noise is governed by Poisson statistics, and so its variance is given by $(\sqrt{S})^2$ (see eq.~(5.9) in the class notes). Putting these all together yields: $\sigma_S^2 = \sigma_F^2 + \sigma_B^2 + \left(\sqrt{S}\right)^2 = \sigma_F^2 + \sigma_B^2 + S$.

The variance in **F** and **B** is

$$\sigma_F^2 = \frac{\left(N_F \sigma_p\right)^2}{N_F} = N_F \sigma_p^2 \quad \text{and} \quad \sigma_B^2 = \frac{\left(N_B \sigma_p\right)^2}{N_B} = N_B \sigma_p^2$$

(see eq.~(5.26) in the class notes). Finally, putting this all together, the variance in **S** is

$$\sigma_S^2 = N_F \sigma_p^2 + N_B \sigma_p^2 + S$$

This yields an estimate of the error in the measurement of **S** of

$$\delta S = \sqrt{\sigma_S^2} = \sqrt{N_F \sigma_p^2 + N_B \sigma_p^2 + S}$$

Error in the instrumental magnitude: Instrumental magnitude is defined as

$$m_i = -2.5 \log_{10}(S/\Delta t) = -2.5 \ln(S/\Delta t)/\ln 10\,,$$

where **S** and Δt are defined as above. To get the error in *m,* Δ*m*, based on the error in **S**, ΔS, we need to propagate our errors (see eq.~(6.7) in the class notes):

$$\delta m_I = \sqrt{\left(\frac{\partial m_I}{\partial S}\right)^2 (\delta S)^2} = \sqrt{\left(\frac{dm_I}{dS}\right)^2 (\delta S)^2} = \left|\frac{dm_I}{dS}\right| \delta S\,.$$

Plugging in for m_I from above,

$$\delta m_I = \frac{2.5}{\ln 10} \frac{\delta S}{S}$$

Summary: The preceding brief discussion succinctly summarizes all the steps necessary to calculate error bars based on your data. Furthermore, it is complete, and contains all the definitions and equations required to go from the output of *phot* to magnitudes with error bars.

Sample code for simple magnitude calculations and plots

The following is a sample of the type of things you might want to do with your data for your project. What follows is only a sample and if used should be tailored to your individual needs. You can copy the following to a file called "batch.pro" and run it by typing:

```
IDL> @batch.pro
```

on the command line. This works as a script as long as you don't use any for or if statements. To run code with these you need to uncomment the line at he beginning of the code that says "pro batch" and at the very end of the file that says "end". You run that by typing in the IDL command line:

```
IDL> .r batch.pro
```

then

```
IDL> batch
```

Each line that is not commented out will be executed.

```
------------------------batch.pro-----------------------
; a semicolin is a comment line

; pro batch
; read the data in from the output file
readcol, 'sample.out', imagename,serial,box, back, object, $
object_back, error,exptime,frametime, format='(a,a,x,x,x,x,x,x,f,f,f,f,f,f,a)', delimiter=','

; calculate magnitude, add 24 so that the numbers are easy and not confusing to deal with
mag = -2.5*alog10(object_back)+24.
print, mag

; calculate the flux errors and convert to magnitude
boxerror = Sqrt(box^2.*error+box^2.*error+object_back)
print, boxerror

magerror = (2.5/alog(10))*(boxerror/object_back)
print, deltamag

; Plot data with no error bar
plot, time, mag, psym=4, xtitle='time (h)', ytitle='instrumental magnitude', title='Sample Plot'

; Plot data with error bar
ploterror, time, mag, magerror,psym=4, xtitle='time (h)', $
ytitle='instrumental magnitude', title='Sample Plot'

; Plot with a specific range (all positive numbers)
plot, [10,15], [2,3], /nodata
oploterror, time, mag, magerror, psym=4
```

```
; Plot with magnitudes, brighter up -- you kind of have to trick it
plot, [0,0], [0,0], /nodata, xrange=[0,10], yrange=[0,-3], $
xtitle='time (h)', ytitle='insturmental magnitude'
oploterror, time, mag, magerror, psym=4

; select a particular serial number and plot it
z=where(serial eq 1)
; make sure there are objects with this serial number, the values that
; come back are indices to your arrays
print, z
ploterror, time[z], mag[z], magerror[z], psym=5

; another example
; make sure your error calculation is correct
z=where(serial eq 0)
y=where(serial eq 1)
ploterror, time[z], mag[z]-mag[y],Sqrt(magerror[z]^2.+magerror[y]^2.), psym=4

; Plot options, PSYM Value
;1 = Plus sign (+)
;2 = Asterisk (*)
;3 = Period (.)
;4 = Diamond
;5 = Triangle
;6 = Square
;7 = X

; end
------------------------batch.pro-----------------------
```