

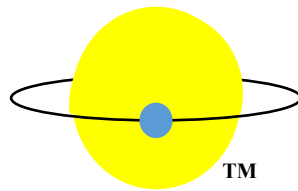
Assignment for the next class:

- (1) Read this document. It is an excerpt from <https://astrodennis.com/Guide.pdf>.
- (2) Download and install AstrolmageJ v 5.0.0.00 from <https://www.astro.louisville.edu/software/astroimagej/>
- (3) Download the 5 sample files (Bias.zip, Darks.zip, Flats.zip, SciencelImages.zip, and Measurements\_Tempate.zip) from <https://astrodennis.com>.

We will process the sample files in the next class. Then will take our own data and use it instead of Dennis's sample data as one of our most significant projects in our remaining four weeks.

# A Practical Guide to Exoplanet Observing

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**by**

**Dennis M. Conti**

**dennis@astrodennis.com**

**www.astrodennis.com**

## 6.1. Preparation Phase

### 6.1.1. File Directories

On the computer that runs the observer's image capture software, it is best to initially setup the following subdirectories: AIJ Analysis, Bias, Darks, Flats, Quarantined Images, and Science Images. The AIJ Analysis subdirectory is where measurement and model fit files from AIJ can be stored. The Bias, Darks, and Flats subdirectories are where the respective calibration files can be stored. The Science Images subdirectory would hold the raw images containing the target star, and the Quarantined Images subdirectory is where "bad" science images due to cosmic ray hits, satellite, tracks, etc. could be parked. If the user wishes to use other names for these subdirectories, then such names may be substituted for their respective counterparts in the examples that follow.

### 6.1.2. Stabilization of Imaging System to Appropriate Temperature

The imaging system should be put in place with enough time for it to reach its desired temperature set-point, which might also require enabling of its cooling system.

### 6.1.3. Generation of Flat Files

Whether twilight flats are taken or flats are generated by using an electroluminescence panel, they should (ideally) be redone prior to or after each imaging session using the same imaging chain as was used for taking the science images, and with the imaging chain not having been displaced or moved. See Section 6.3.2 for guidelines on creating flats.

### 6.1.4. Autoguiding

Autoguiding should be used during the Imaging Phase below, unless the observer's mount is of such accuracy that it can maintain guiding within a few pixels for the duration of the transit observation (where the actual value of "a few" depends on the FWHM of the host star). See Section 4.4 above for an overview of various autoguiding techniques. The observer's auto-guiding mechanism should be calibrated, if not yet done or if the auto-guiding software does not automatically correct for changes in declination. If needed, calibration should also be done for any active optics (AO) system that is being used.

## 6.2. Imaging Phase

### 6.2.1. Choice of Binning

The FWHM of stars in the target field should be spread out over 3-5 pixels. If the imaging camera is normally setup to bin more than 1x1, binning might have to be reduced to achieve this. This then would result in an acceptable image scale (sometimes called “plate scale” or “pixel scale”). Image scale is expressed in arc-seconds per pixel and is a function of the focal length of the telescope and the size of the CCD photosite. For example, assume that the FWHM is 3.0 arc-seconds, and the unbinned image scale of the observer’s imaging system is 0.5 arc-seconds/pixel. This means that, without binning, the FWHM would be spread over 6 pixels and that 2x2 binning would mean that that the FWHM would be spread over 3 pixels, still within the acceptable, albeit the lower, part of the range.

Stars should be brought into precise focus if for no other reason than to get an accurate measure of FWHM. However, if the target star is too bright and could saturate the imaging camera, it may be necessary to defocus the OTA. If the sky background is not too high, defocusing that results in a PSF of 10-20 pixels is acceptable, as long as this defocusing doesn’t result in the flux of a nearby star blending with the target star’s flux.

### 6.2.2. Choice of Exposure Time

The optimal exposure time is one that maximizes the target star’s SNR, while not saturating the imaging camera’s detector. For a given target star, factors that affect the optimal exposure time include:

1. the telescope’s aperture size,
2. the filter used,
3. the quantum efficiency (QE) of the imaging camera,
4. whether the star is rising to the local meridian, or has passed the meridian and is falling,  
and
5. seeing conditions.

Today’s CCD detectors typically have a linear range up to a point, after which they become non-linear and then, at some point they become saturated. At its saturation point, any additional photons hitting the CCD photosite will not be registered. Thus, it is critical that the target and comp stars never reach saturation and ideally not reach non-linearity as well (it should be noted, however, that software such as AIJ does provide a facility for making non-linearity corrections). It is important that the exposure time be chosen such that a decent SNR is achieved, but not long enough that neither non-linearity nor saturation occurs. If the target star is predicted to rise toward the local meridian and, therefore its light will pass through less and less air mass, either of these two situations could occur. Thus, the observer should also take this into consideration when choosing an exposure time. Note that defocusing could also help this situation.

In order to initially set the correct exposure time, a series of test images should be taken with increasing exposure time. The SNR of the target star, as well as its ADU counts, could then be measured for each exposure setting. Section 7.5.1 describes how AIJ can be used to determine a star's SNR. An exposure setting that maximizes SNR, but doesn't present a potential for saturation during the imaging session should then be considered as the ideal exposure time.

The following best practice procedure conducted immediately prior to the actual observing session is recommended to determine the optimal exposure time:

1. At the target star's current sky position, take test images at various exposure times. First, select the exposure time with the greatest SNR for the target star where the peak ADU count is less than 75% of the saturation point of the imaging camera's detector. Note: this 75% limit may have to be reduced if the camera is expected to reach non-linearity much earlier.
2. If the star will be rising toward the local meridian, reduce the exposure time such that the detector will not reach saturation.
3. If the star will be falling from the local meridian, increase the exposure time such that the peak ADU count of the target star is equal to 75% of the saturation point of the detector.

There are some situations where the professional science team might require a certain cadence of images to be taken, which might be at the expense of the (longer) optimal exposure time. This may be the case where finer details of the pattern of the light curve are more important than the accuracy of the light curve depth itself. Also, to confirm some false positive scenarios, it may be necessary to increase the exposure time, and therefore the SNR, of faint stars near the original target, at the expense of possible saturation of the target.

### 6.2.3. Time Synchronization

Because of the natural drift in the image capture computer's clock, it should be frequently synchronized with the U.S. Naval Observatory's Internet time server. This can be done using (freeware) software such as Dimension 4 (see <http://www.thinkman.com/dimension4/>). The update period for such clock synchronizations should be set to at least every 2 hours.

### 6.2.4. Time System

Because of the existence of several different time systems, the exoplanet observer should be aware which one is being used for the transit prediction, which one is being entered into the image FITS headers, which one is being used during the light curve modeling process, etc. The more commonly used time systems are:

- a) Julian Date/Universal Coordinated Time ( $JD_{UTC}$ ),
- b) Heliocentric Julian Date/Universal Coordinated Time ( $HJD_{UTC}$ ),
- c) Barycentric Julian Date/Barycentric Dynamical Time ( $BJD_{TDB}$ ).

If the results of the exoplanet observation are to be used in a professional/amateur collaboration,  $BJD_{TDB}$  would be the desired time standard to use during the model fitting process. Sections 7.2.2 and 7.6 describe how AIJ can convert the time of the captured images to  $BJD_{TDB}$  time.

### 6.2.5. Operating Temperature

The imaging system should be put in its operating environment with enough time for it to reach as low a temperature set-point as possible, which might also require enabling of its cooling system.

### 6.2.6. Image Capturing

The observer's normal image capture software is used to capture the science images into the Science Images subdirectory during this phase. Should a meridian flip be necessary during the imaging session, then at the time the meridian flip is needed, the observer should:

1. Abort the image capture software
2. Stop autoguiding
3. Execute the meridian flip
4. Reposition the target star as necessary in the camera's field-of-view
5. Enable autoguiding
6. Enable the image capture software.

## 6.3. Image Calibration Phase

### 6.3.1. Calibration Files

Prior to or after the capture of science images, the user would also capture a series of darks, flat field, and bias calibration files and store them in their respective subdirectories. A rule of thumb is to (ideally) capture an odd number of images for each such calibration series. An odd number is suggested, since this better allows for a median combine to later be used to create the master dark, master flat, and/or master bias files. In any case, at least sixteen (16) images should be captured for each calibration file type.

Guidelines for exposure times for each of these calibration file types are as follows:

1. Dark files – exposure time should equal that of the science images and should be taken at the same temperature as were the science images.
2. Flat field files – exposure time is dependent on the flat fielding technique used, but typically takes 3 seconds or less. However, this exposure time may have to be increased for cameras with automatic shutters so that no shutter shading occurs. A rule of thumb is to create flat field frames such that the resulting histogram is mid-way within the dynamic range of the CCD detector. For example, for a detector with a typical maximum

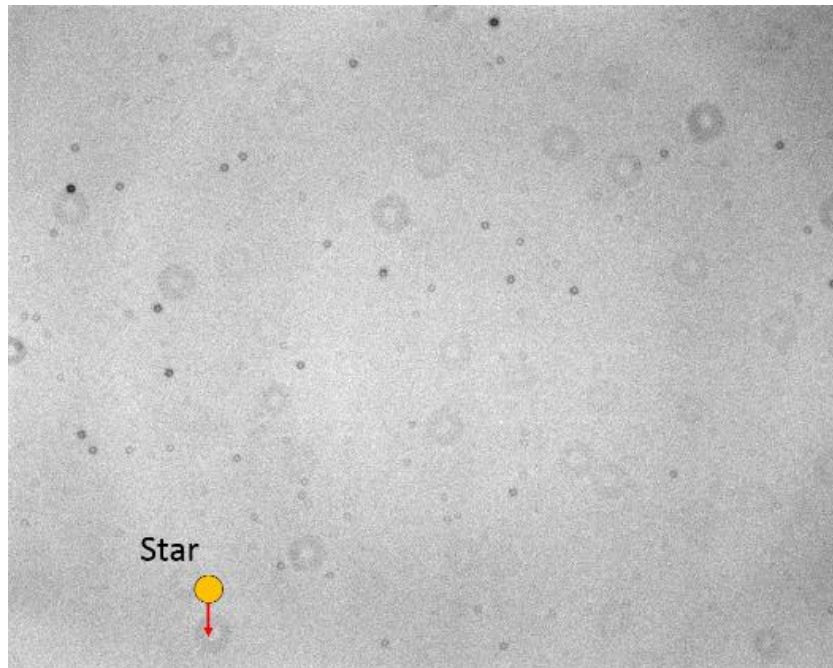
ADU count of 65,000, the brightness of the light source would be set such that the center of the resulting histogram is at 32,000 ADUs. As discussed in Section 6.3.2 below, special consideration is needed for the creation of flat files.

3. Bias files – a bias file is a dark file of 0 second exposure time.

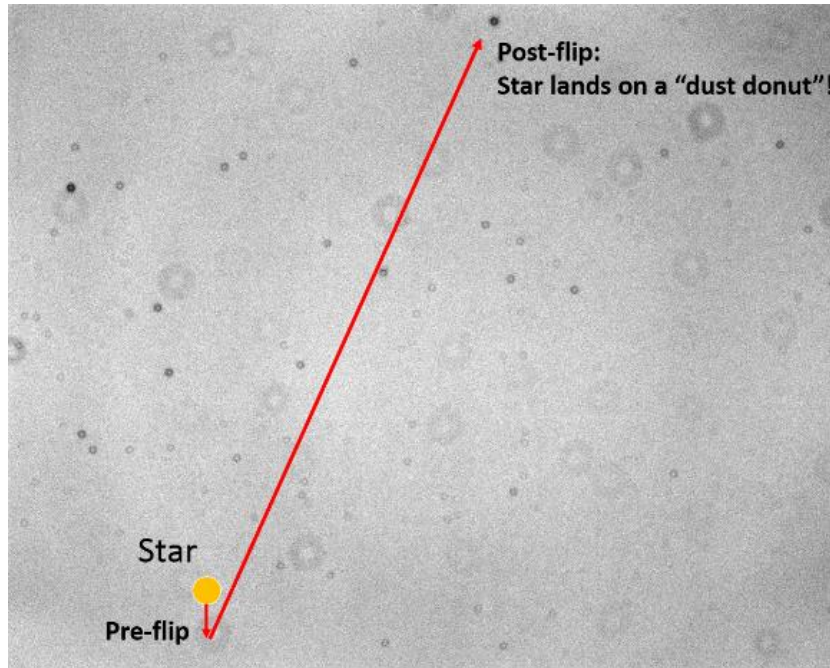
Typically, flat dark files are also created since the flat fields themselves contain dark current that needs to be subtracted out. When used, “flat darks” are taken at the same exposure time as the flat field files themselves. However, as seen in Section 7.2 below, a technique employed by AIJ that can scale the Master Dark to the same exposure time as the Master Flat obviates the need for the user to generate flat dark files.

### 6.3.2. Flat Fielding Techniques

Because star movement over a few pixels is inevitable even with autoguiding and fairly accurate polar alignment, flat field correction is relied upon to mitigate the effects of dust donuts and vignetting. Poor flat fielding is one of the major contributors to systematics. For example, Figure 1 depicts a flat field and the potential movement of a star onto a nearby dust donut. Figure 2 depicts what would happen in the case of a meridian flip, namely the star would flip across the diagonal of the detector and possibly land on another dust donut. If flat field correction is not performed for either of these two cases, the flux of the star in question would artificially change.



**Figure 1. Star Movement in an Uncorrected Flat Field**



**Figure 2. Star Movement after a Meridian Flip**

Flat fields should ideally be created before or after each observing session, and certainly when there is any change in the imaging chain.

The following are common techniques for generating flat fields from which a master flat can then be created:

1. Twilight flats – flats are taken at dawn and dusk. Because of the speed that sky lighting conditions change, it is often cumbersome to take a good set of flats, especially if this has to be done for multiple filters. In some cases, the flats may show stars if the exposure time is too long. Homemade diffusers using a white T-shirt have been a popular way to mitigate this problem.
2. Light boxes – homemade light boxes have been used by some amateur astronomers to create flats. However, using this technique to produce a uniform light field is sometimes challenging.
3. Electroluminescence panels - although at some cost, the technique has several advantages: it can create a relatively good uniform light field, its brightness can be changed to accommodate different filters, and flats may be taken at the observer's convenience.
4. Observatory flats – this technique used in permanent observatories consists of the telescope being pointed to a lit white panel on the wall of the observatory. The efficacy of this technique varies widely with the nature of the white panel, ambient lighting, etc.

### 6.3.3. Creation of Master Files

Image calibration eliminates the effects of the following underlying factors that affect the precision of the measurements: bias, dark current, and dust donuts and vignetting. The following are best practices for dealing with each of these factors:

1. Bias files should be taken at some time before or after the observing session. These are then used to create a master bias file, ideally using median combine.
2. Dark files should best be taken at the end of the observing session. The reason for taking them at the end of the observing session is to make sure that they are taken at the same temperature as the science images. A master dark file is then created from them, again using median combine.
3. Flat files should be taken either at the beginning or end of the observing session. Since flat files themselves have dark current and are at a different exposure time than the science images, they need to have dark current removed. Rather than creating a master dark specifically to make dark correction for the flats, another approach is to use the same master dark file created for the science images, but scale it to the exposure time of the flat files. Software such as AIJ, has such a scaling feature. Section 6.3.2 above describes the best practices for creating flat files.

### 6.3.4. Updating FITS Header Information

During the image calibration phase, some software packages such as AIJ allow the user to update the FITS headers in the science images with information such as the equivalent  $BJD_{TDB}$  times of the observation. If not included in the FITS header by the image capture software, other important information such as AIRMASS can be included as well. As will be seen later, AIRMASS is one of the more commonly used detrend parameters during the transit modeling process.

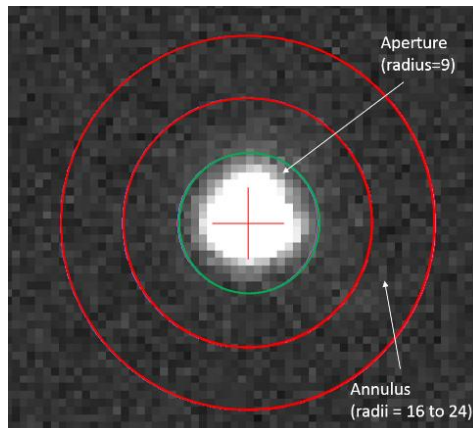
## 6.4. Aperture and Differential Photometry Phase

As was mentioned in Section 3, the exoplanet transit method is all about comparing the relative change in brightness between the target star and a set of suitable comparison stars. Before this comparison can be done, however, the brightness of each star needs to be adjusted for any photon counts due to the background sky that might be affecting each particular star. This is done using aperture photometry. Once this is done, the relative change in (adjusted) flux between the host star and the comparison stars can then be obtained. This process is called differential photometry. The best practices associated with aperture and differential photometry are described below.



### 6.4.1. Aperture Photometry

Aperture photometry involves defining both the “aperture” of a certain radius around a star, as well as an outer “annulus.” The idea of the annulus is to measure the sky background around the star. Figure 3 depicts an aperture of radius 9 and an annulus starting at 16 pixels from the centroid of the star and ending at pixel location 24.



**Figure 3. Aperture and Annulus**

In order to compensate for background sky contribution, the ADU counts per pixel in the annulus are used to adjust the ADUs in the aperture. Some software such as AIJ also has the ability to detect and adjust for any faint stars that might happen to be in the annulus and therefore bias the background sky counts. As will be described later, the radii settings initially set for the aperture and annulus may be changed after an exoplanet model fit is done to further optimize the fit.

Section 7.5.1 describes how AIJ can be used to select the initial size of the aperture and annulus.

### 6.4.2. Differential Photometry

Differential photometry involves applying aperture photometry on the target star and multiple comparison stars and then comparing the relative differences in (adjusted) flux. The following are the best practices for selecting suitable comparison stars:

1. Ideally, at least 8 comparison stars should be chosen whose magnitudes are as close as possible to that of the target star – i.e., no greater than 0.75 in magnitude (i.e., fainter) and no less than 0.44 in magnitude (i.e., brighter) than the target star. If this is not possible, then an ensemble of comparison stars should be selected such that the average of their aperture counts is close to that of the target star. Also, when trying to determine if there are any sources causing a false positive, the observer may be instructed to test for the occurrence of a transit event for all stars within a specified radius of the target star.
2. The comparison stars should ideally be of similar stellar type to the target star in order to minimize the differences in atmospheric extinction. However, if the transit modeling software is able to “detrend” the effects of AIRMASS, such as is possible with AIJ, then

choosing comparison stars of similar brightness to the target star is more important than choosing stars of similar stellar type.

3. The comparison stars should not be inherently variable. This can later be determined by viewing the light curve of each comparison star as described in the next section, or by using information from the AAVSO's Variable Star Plotter utility (AAVSO, 2017).

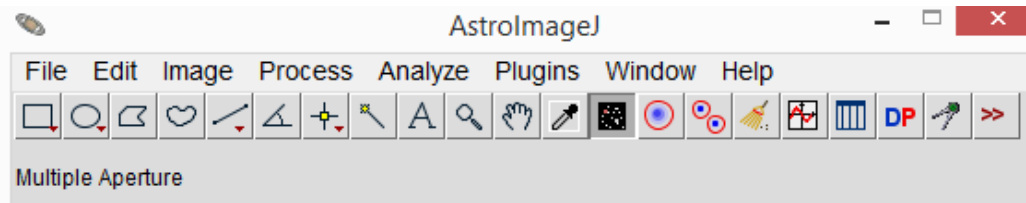
The results of the differential photometry phase will be a Measurements file that has, as a minimum, for each image: the timestamp of the image, the change in flux or magnitude of the target star (relative to the comparison stars), and its associated errors. Depending upon the differential photometry software, other valuable data could include the relative change in flux or magnitude of each comparison star (relative to all the other comparison stars), their associated errors, and changes in the X,Y pixel coordinates of the target and comparison stars.

## 7. Using AstroImageJ

The rest of this Guide describes the use of AIJ for the post-processing of science images and for conducting exoplanet model fitting. The use of AIJ assumes that the user has already installed AIJ and has read the AIJ User Guide, available at:

<http://www.astro.louisville.edu/software/astroimagej/>.

The user is encouraged to regularly check for an AIJ software update. This is done by clicking on Help in the upper right corner of the main AIJ Toolbar (see Figure 4) and then selecting "Update AstroImageJ...". An "Upgrade To" box then appears. **IMPORTANT:** If a daily build exists, please load it. This can be found by going UP in the Upgrade To box.



**Figure 4. AIJ Toolbar**

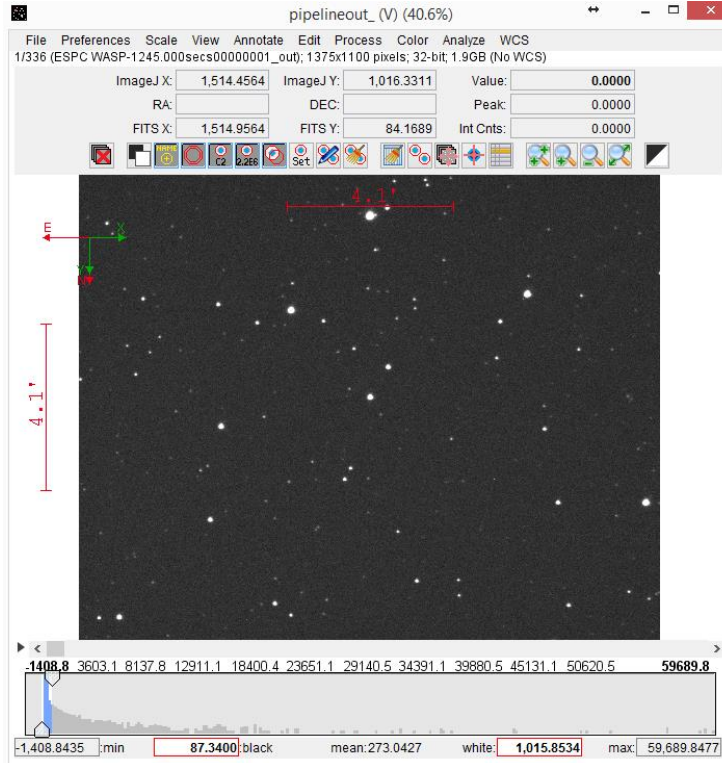
Data from actual exoplanet transits will be used in the examples throughout the rest of this Guide. Both the calibration files and original images for the WASP-12b example can be found at <http://astrodennis.com>.

### 7.1. Loading Images into AIJ

A single image or a sequence of images can be loaded into AIJ.

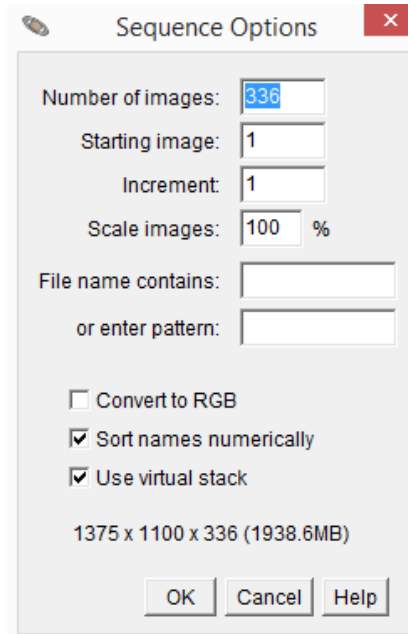
To open a single image, select File->Open from the AIJ Toolbar (Figure 4) and then select the desired file. The Image Display screen (see Figure 5) then appears. One example of useful

information that can be obtained from any one of the science images are the contents of its FITS header. This information can be obtained by selecting Edit->FITS header on the top of the Image Display screen. Many of the operations on the Image Display Screen that are described below for a sequence of images can also be applied to a single image.



**Figure 5. Image Display Screen**

A set of images can be loaded into what is called an AIJ “stack.” Each image in the stack is called a “slice.” The stack is an active set of images that various AIJ functions can be applied to. From the AIJ Toolbar select File->Import->Image Sequence. For Windows users, then select ONE file in the subdirectory containing the calibrated science images (note: do not try to select a range of images; it is necessary only to select one of the files in the subdirectory). For MAC users, select the subfolder containing the desired images to be displayed. A screen similar to the one in Figure 6 appears.




**Figure 6. Sequence Options Screen**

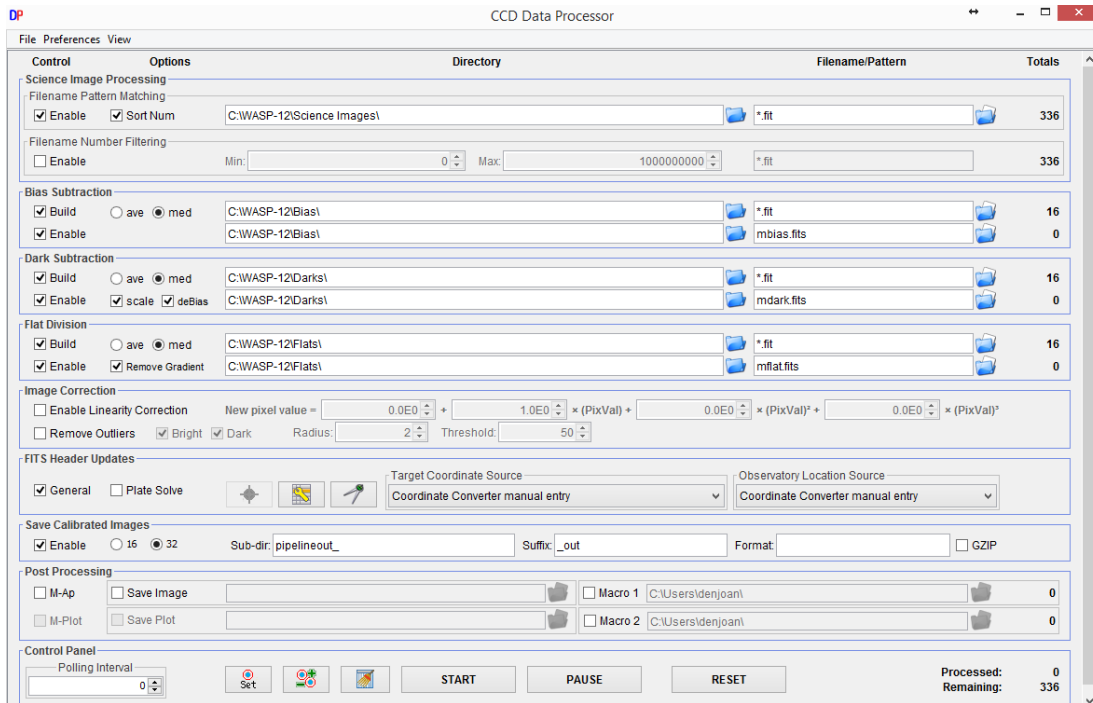
If the computer running AIJ has sufficient memory to hold all images in the stack, then the “Use virtual stack” selection on the Sequence Options screen can be unchecked, thereby causing AIJ to run faster since the images can be directly accessed from memory. If an out-of-memory message appears in this case, then more memory can be allocated to AIJ by performing the following:

1. From the main AIJ Toolbar, go to Edit->Options->Memory and Threads...
2. Change the Maximum memory value to a larger value.

Next, with the boxes checked as in Figure 6, with the possible exception of the virtual stack selection, select OK. This creates an AIJ stack of the calibrated science images. The Image Display (Figure 5) then shows the first image in the stack.

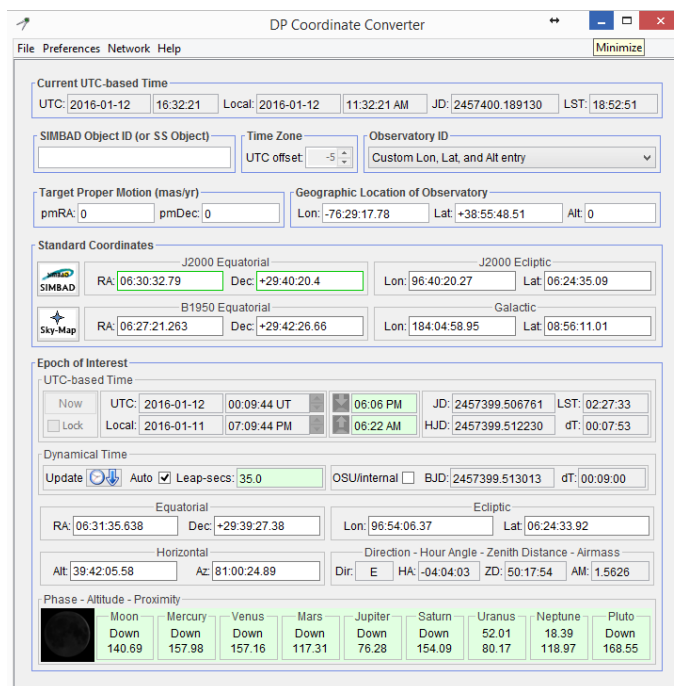
## 7.2. Calibrate Science Images

The Data Processing (DP) function of AIJ can first be used to calibrate the science images taken during the Imaging Phase. Note: Before proceeding with this section, it is strongly suggested that the reader review Section 6 (DP User Interface) of the AIJ User Guide. The DP function is initiated by clicking on the  icon from AIJ’s main Toolbar. Figure 7 is an example of one of the two screens that then appears.



**Figure 7. CCD Data Processor Screen**

An example of the other screen that appears is depicted in Figure 8, which may initially be covering the CCD Data Processor Screen.



**Figure 8. DP Coordinate Converter Screen**

The purpose of the CCD Data Processor screen is to calibrate the science images using the bias, dark, and flat field files previously captured. There are several ways, however, in which the master bias, dark, and flat files used for calibration can be created. For example, the master files can be created in separate runs of the CCD Data Processor, and then one final run specifies the master files being used. In addition, the user may use other programs for accomplishing the calibration and may simply decide to use AIJ to just update the FITS headers of the calibrated files, which process is described below. In the example depicted in Figure 7 and described below, AIJ uses one run to accomplish everything: master files are first created from individual bias, dark and flat files, these master files are then used to calibrate the 336 science images, and, finally, the FITS headers of the resulting calibrated files are updated. In the example below, the original dark files and science images had an exposure time of 45 seconds and the flat field files had an exposure time of 3 seconds.

### 7.2.1. Specifying Science Images and Calibration Files

The first step in conducting image calibration is to specify where AIJ can find the science images and the calibration files.

Under the Science Image Processing section on the CCD Data Processor screen, the “Enable” and “Sort Num” boxes are checked and the directory is entered where the science images reside (this can also be done by clicking on the folder icon and selecting the appropriate subdirectory). Next, the appropriate file extension with the wildcard indicator “\*” for the filename path is entered. If the filename path and extension for the science images have been properly entered, then the Totals count to the right should be correct.

The above method should also be used for specifying the subdirectories and file extensions for the bias, dark and flat files. For each of these sets of calibration files, a subdirectory and full filename (not just extension) should be entered for their respective to-be-created master files. For example, in Figure 7, a master dark called mdark.fits will be created in the same subdirectory where the individual darks are found.

The Build and Enable checkboxes for each of the calibration types should also be checked, and the choice made for whether average (ave) or median (med) combine should be used to create the masters. If the darks are to be scaled and used as flat darks, then the “scale” and “deBias” boxes should be checked.

There are variations to the above. For example, to use already created masters, the “Build” boxes do not have to be checked.

Note: It is important that the “Remove Outliers” option is NOT selected when differential photometry is being done and that the Polling Interval under the Control Panel is set to 0. Also, unless the “Enable” option for Filename Number Filtering or the “Enable Linearity Correction” option are being used (see Section 6.3.2.1 and Section 6.3.2.5, respectively of the AIJ User

Guide), then they should not be enabled.

### 7.2.2. Updating FITS Header Information

AIJ has two methods for obtaining some essential information such as AIRMASS,  $BJD_{TDB}$  times, etc., which will be useful during the Photometry, Plotting, and Modeling Phase. The first method is to update the Measurements file that is created after differential photometry has been applied to the calibrated images. This method is described in Section 7.6 below. This method, however, does not update the FITS headers of the calibrated files, so each time a new differential photometry measurement is performed on the calibrated images, this update would have to take place again. It should be noted that some camera capture software will include AIRMASS in the FITS header, but most likely not  $BJD_{TDB}$ .

The second method, which occurs during the Calibration Phase, is to include this information directly in the FITS headers of the calibrated files. Thus, at the time the calibration files are being corrected with any bias, darks, and flats, their FITS headers are being updated as well. With this method, multiple modeling runs can be made with different photometry settings, without having to update the Measurements file after each run with information such as AIRMASS and  $BJD_{TDB}$  time.

To update the FITS headers during the calibration process, the user should select General under the FITS Header Updates section of the CCD Data Processor screen (see Figure 7). The DP Coordinate Converter Screen then appears (Figure 8), if it isn't already open.

To update the FITS headers, AIJ needs the RA and DEC coordinates of the target, as well as the location where the observation was conducted. This information can be manually entered, or AIJ can automatically extract this data from the FITS headers if it was included there by the user's image capture software.

#### 7.2.2.1. Entry of Target and Observation Location Information

In the case of manual entry of the target's coordinates and/or the observation location, the user would select "Coordinate Converter manual entry" under either or both the Target Coordinate Source box and the Observatory Location Source box. On the DP Coordinate Converter screen, the user would then enter the Lon (Longitude), Lat (Latitude), and Alt (Altitude) fields in the Geographic Location of Observatory section and/or enter the target's RA and DEC fields in the J2000 Equatorial section. A description of how the user can create an entry for the user's observatory, in a list of pre-defined observatories, can be found under "Customize Observatory Data," which can be reached from the Help tab on the DP Coordinate Converter screen. The user can then later access this stored information via the Observatory ID pull-down list on the DP Coordinate Converter screen in order to automatically populate the entries for the Geographic Location of Observatory.

If RA and DEC coordinates are already part of the image's FITS header, the user would select "FITS header target RA/DEC (2000)" under the Target Coordinate Source box. If the observation location is already part of the image's FITS header, the user would select "FITS header longitude and latitude" under the Observatory Location Source box.


#### 7.2.2.2. Dynamical Time Updates

No matter which method is used by AIJ to obtain the target's coordinates and the observation location, the user should select Auto under the Dynamical Time section of the DP Coordinate Converter Screen. This will allow AIJ to account for the appropriate number of additional leap seconds when it is doing its time conversions to  $BJD_{TDB}$ .

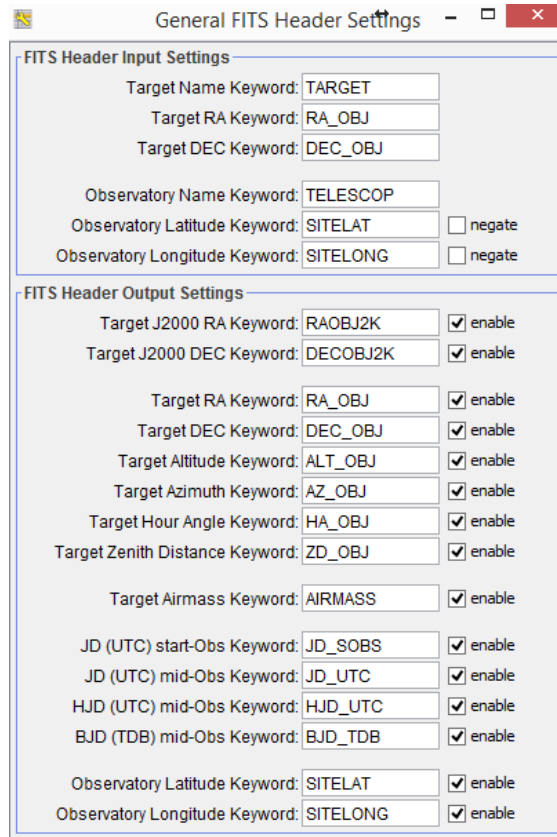
#### 7.2.2.3. Other Required FITS Header Information

Next, it is important that the raw science images have information in their FITS headers about the date/time of the start of the observation, as well as the exposure time. Sections 6.3.2.6.1 and 6.3.2.6.2 of the AIJ User Guide describe the acceptable FITS header keywords that AIJ can use to obtain this information.

#### 7.2.2.4. FITS Header Settings

Once the above observatory and target information is filled in, and it is confirmed that the FITS headers contain acceptable date/time and exposure information, then the user would select the  icon on the CCD Data Processor screen. The General FITS Header Settings screen then appears (Figure 9).





**Figure 9. General FITS Header Settings Screen**

If the automatic entry method was used for the target coordinates, then the appropriate keywords in the image’s FITS header associated with this information should be included in the Target RA Keyword and Target DEC Keyword entries under the FITS Header Input Settings portion of the screen (see Figure 9). Common keyword pairs for this information are: RA\_OBJ, DEC\_OBJ and OBJCTRA, OBJCTDEC; however, the user should confirm which keyword pair is placed in the images’ FITS header by the user’s image capture software.

Likewise, if the automatic entry method was used for the observation location, then the appropriate keywords in the image’s FITS header associated with this information should be included in the Observation Latitude Keyword and Observation Longitude Keyword entries. SITELAT and SITELONG are such keywords. NOTE: some image capture software, such as SkyX Pro, might put a positive number in the FITS header for longitude even though it is West longitude (West longitude is typically shown with a negative sign, unless it is expressed as Elongitude – namely, total degrees from 0 longitude.). If West longitude is a positive number in the user’s FITS header, then the user should check the “negate” box to indicate to AIJ that the number found in the FITS header should really have a negative sign associated with it.

The FITS Header Output Settings portion of the screen indicates which items will be added to the calibrated images (indicated by those that have “enabled” checked). Note: it is suggested that all the default keywords stay as “enabled.”

**IMPORTANT:** If an AIJ update is performed, the user is advised to make sure that the entry for the “BJD (TDB) mid-Obs Keyword” on the General FITS Header Settings screen is set to BJD\_TDB (earlier versions of AIJ set this entry value to BJD.UTC).

#### 7.2.2.5. WCS Information

Finally, although not done in this example, the World Coordinate System (WCS) coordinates for each star in each image can be obtained by selecting the Plate Solve option on the CCD Data Processor Screen. It should be noted, however, that this process could take a long time and in many cases is not necessary (see Section 7.4 below for obtaining WCS coordinates for selected images).

#### 7.2.3. Begin the Calibration Process

Using the above as an example, when the START button is selected, the DP routine will automatically perform the following steps:

1. Create a Master Bias (mbias.fits) from the 16 bias files.
2. Create a Master Dark (mdark.fits) from the 16 dark files. Correct this Master Dark with the Master Bias. Thus, the Master Dark will have bias removed from it.
3. Create a Master Flat (mflat.fits) using the 16 flat files in the following manner:
  - a. first calculate a scaling factor that represents the ratio of the exposure times of the flat fields to the exposure time of the original dark files (in this example, the scaling factor would be  $0.0667=3 \text{ sec}/45 \text{ sec}$ );
  - b. perform bias correction using the Master Bias;
  - c. perform dark correction using the Master Dark, scaled with the scaling factor;
  - d. remove gradients;
  - e. normalize the calibrated flats.
4. The FITS headers of the calibrated files are updated.
5. Calibrate each science image using the resulting Master Bias, Master Dark, and Master Flat. An Image Display is seen for each image as it is being calibrated.
6. The calibrated science images are stored in a calibration subdirectory under the subdirectory that held the Science Images. In this example, the subdirectory will be called pipelineout and its files will have a suffix of \_out. Note: it is best to check the 32 bit

option for these saved calibrated files.

#### 7.2.4. Real-time Operation

In addition to conducting image calibration after the observation, AIJ is also capable of operating “in real-time” if the Polling Interval is set to a non-zero value and the appropriate options are selected in the Post Processing section. In this case, at the specified Polling Interval rate, AIJ will automatically check the science image directory for newly added files that match the file pattern matching and number filtering criteria specified on the CCD Data Processor screen. AIJ will then calibrate them, will optionally conduct differential photometry on them, and will optionally update the light curve (see the checkboxes under Post Processing on the CCD Data Processor screen for selecting these options).


#### 7.2.5. Additional Options

Section 6 of the AIJ User Guide provides other options available for the CCD Data Processor screen.

### 7.3. Loading Calibration Images

After calibration, the images in the calibration subdirectory can be loaded into AIJ (see Section 7.1 on how to load a set of images).

In order to make sure that the field-of-view (FOV) indicators are correct for both the vertical and horizontal axes on the Image Display Screen for the calibration images, the correct X and Y pixel scales should be set. Pixel scales will have been set correctly if WCS coordinates were already found by using either the Plate Solve option on the CCD DP Processor screen (see Section 7.2.2.5) or one of the WCS->Plate solve options on the Image Display screen (see Section 7.4). Alternatively, correct pixel scales can be manually entered by selecting, at the top of the Image Display Screen, “WCS->Set pixel scale for images without WCS...”, and then entering the correct X and Y pixel scale values.

The slider below the image can then be used to move through all the images in order to find ones that should be eliminated due to excessive cloud cover, poor guiding, or other anomalies. If images show increasing degrees of misalignment, see Section 7.5.3 how to correct for this. Poor images can be deleted by bringing up that particular image on the Image Display and then simply selecting the “delete currently displayed slice”  icon in the upper left of the Image Display. Alternatively, Edit->Stack->Delete can be selected from the menu bar on the Image Display. It is advisable, however, to move such poor images from the calibration subdirectory where they reside to a separate “Quarantined Images” subdirectory. This is so that if the differential photometry needs to be redone on files in the calibration subdirectory, then the user does not

have to go through this image elimination process again.

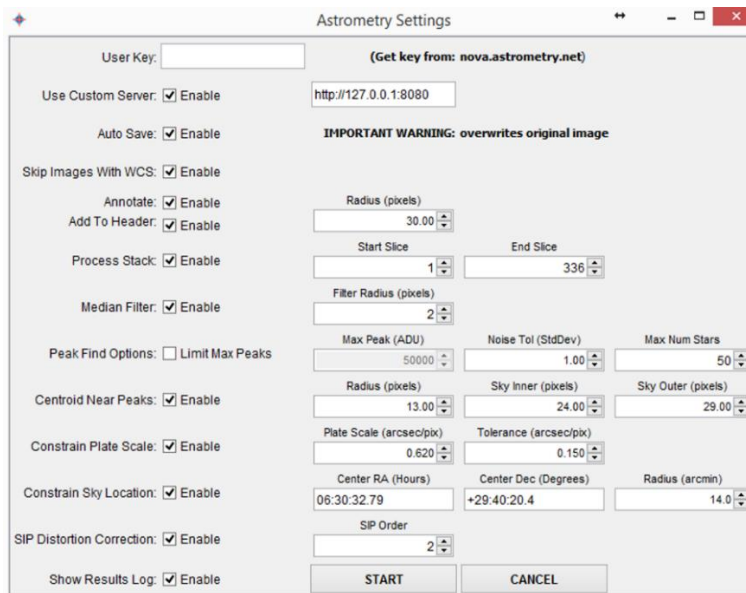
#### 7.4. Plate Solving Using AIJ

Plate solving means associating stars in an image with their RA and DEC coordinates. Optionally, this information can also be permanently stored back into the image's FITS header for possible later use. The information stored in the FITS header uses WCS information; this information allows subsequent runs to identify the RA and DEC coordinates of selected stars.

The following are examples where it might be desirable to use one or more plate solved images:

1. it may be useful to plate solve an image to locate the exact location of the target star in a crowded field of stars;
2. if images are misaligned throughout the observing session, or a meridian flip has occurred, it may be useful to track the location of particular stars from one image to the next during the differential photometry process using their RA and DEC coordinates.

Images that contain WCS information from other software can be used by AIJ, or AIJ itself can be used to plate solve one or more images in the image stack. This is done by selecting from the Image Display menu “WCS->Plate solve using Astrometry.net (with options)...” A screen similar to the one in Figure 10 then appears.



**Figure 10. Astrometry Settings Screen**

AIJ can then use either the online astrometry.net facility for plate solving, or Windows users can use a local version that does not require an online connection. The following describes each of these alternatives.

### 7.4.1. Astrometry.net Alternatives

#### Alternative 1: Plate Solving Using the Online Version of Astrometry.net

For this alternative, an Astrometry.net key is first obtained. This is done by logging in at [http://nova.astrometry.net/signin/?next=/api\\_help](http://nova.astrometry.net/signin/?next=/api_help) using, for example, the user's Yahoo login information. The key can then be found under My Profile. It is called "my API key." This key is then entered into the User Key field on AIJ's Astrometry Settings Screen.

#### Alternative 2: Plate Solving Using a Local Version of Astrometry.net

Windows users can use an alternative to the online version of astrometry.net to perform plate solving. In this case, AIJ uses a local astrometry.net server. The server, developed by Andy Galasso, is called ansvr. It can be installed by going to <http://adgsoftware.com/ansvr/> and following the installation instructions there. Once installed, plate solving can be done locally by enabling "Use Custom Server" on the Astrometry Settings Screen (see Figure 10).

### 7.4.2. Astrometry Information

After the appropriate alternative for invoking astrometry.net is chosen, the following other entries should be made on the Astrometry Settings Screen:


1. "AutoSave" should be checked if the user wishes that the FITS headers of the original image files are to permanently updated with the appropriate WCS information.
2. Selection of the "Annotate" option allows AIJ to draw around stars found in SIMBAD, a circle of size "Radius (pixels)," along with an annotation of the star name. If selected, "Add To Header" will cause these annotations to be added to the image's FITS header.
3. The slice number(s) of the image(s) in the stack to be plate solved should be entered in the Start Slice and End Slice fields.
4. The radii of the aperture and annulus settings that will be used during the differential photometry process (see Section 7.5.1 below) should be entered in the Radius, Sky Inner, and Sky Outer fields.
5. The correct Pixel Scale value for the user's imaging system should be then be entered, as well as some tolerance for its precision.
6. Next, the approximate RA and DEC coordinates of the center of the image, as well as some search radius for suitable stars that can be used during the plate solve process. The user might try first starting with the width of the image, and then reduce it from there.
7. All other values and checkboxes can be set as they appear in Figure 10. When START is selected, the plate solving process will begin

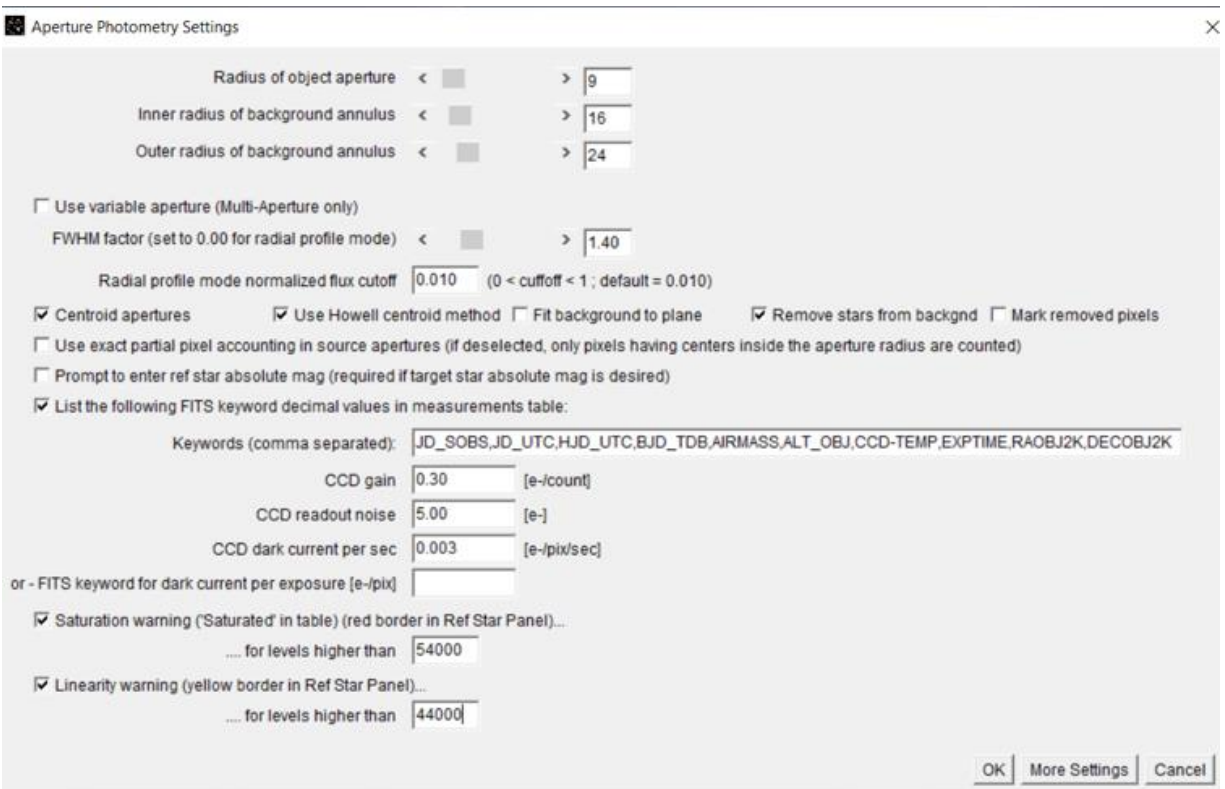
## 7.5. Conduct Differential Photometry

With known candidate comp stars, differential photometry can take place on the images in the stack. See Section 6.4.2 for guidelines on selecting suitable comp stars.

### 7.5.1. Select Appropriate Aperture and Annulus Settings

The first step is to define the appropriate radius of the aperture and the radii of the inner and outer rings of the annulus. This is done as follows:

The  icon on the Image Display screen is selected causing the Aperture Photometry Settings screen to be displayed (Figure 11).



Aperture Photometry Settings

Radius of object aperture <  >

Inner radius of background annulus <  >

Outer radius of background annulus <  >

Use variable aperture (Multi-Aperture only)

FWHM factor (set to 0.00 for radial profile mode) <  >

Radial profile mode normalized flux cutoff  (0 < cutoff < 1; default = 0.010)

Centroid apertures  Use Howell centroid method  Fit background to plane  Remove stars from backgnd  Mark removed pixels

Use exact partial pixel accounting in source apertures (if deselected, only pixels having centers inside the aperture radius are counted)

Prompt to enter ref star absolute mag (required if target star absolute mag is desired)

List the following FITS keyword decimal values in measurements table:

Keywords (comma separated):

CCD gain  [e-/count]

CCD readout noise  [e-]

CCD dark current per sec  [e-/pix/sec]

or - FITS keyword for dark current per exposure [e-/pix]

Saturation warning ('Saturated' in table) (red border in Ref Star Panel)...

.... for levels higher than

Linearity warning (yellow border in Ref Star Panel)...

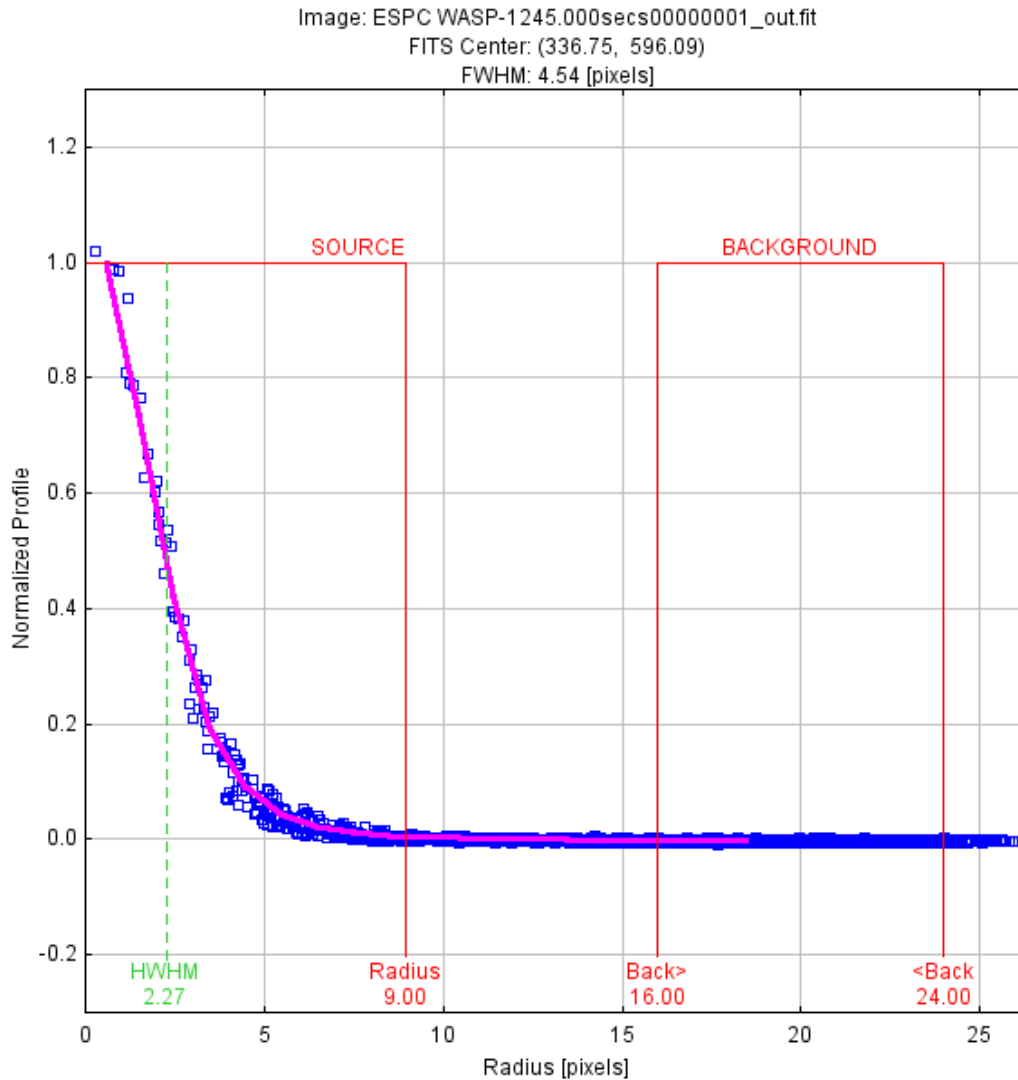
.... for levels higher than

OK More Settings Cancel

**Figure 11. Aperture Photometry Settings Screen**

The initial radii of the aperture and annulus can then be appropriately set using any one of three methods.

Method 1. The initial radii settings can be determined using the Seeing Profile screen associated with the target star (see Figure 12). This screen appears when the cross-hairs is placed on the target star and the user holds the ALT key down while clicking on the star (note: that ALT-clicking the star does not keep the cross-hairs on the star). The radius shown for the Source and the beginning and ending values for the Background can then be used for the initial aperture radius, and the inner and outer annulus radii settings, respectively.





**Figure 12. Seeing Profile Screen**

Method 2. The initial radii can also be determined according to the following guidelines (note that AIJ's automatic selection of recommended values via Method 1 is consistent with these guidelines):

1. The initial radius of the aperture ( $r_1$ ) should be at least 2 times the number of FWHM pixels.
2. The initial radius of the inner annulus ( $r_2$ ) should be chosen such that it and the radius of the outer annulus create an annulus region that excludes any other stars that happen to be close to the target star.
3. The initial value of the outer annulus radius should equal the  $\text{SQRT}(4*r_1^2+r_2^2)$ . This formula should produce an annulus that contains 4 times the number of pixels that are in the aperture.

Method 3. Finally, the initial aperture/annulus settings can be determined by using the ones that maximize the SNR of the target star. AIJ can be used to determine the SNR of the target star in the following manner:

1. Click on the Set aperture settings icon  on the Image Display screen. Set the aperture and annulus radii to some initial settings and then click on OK.
2. Click on the Single Aperture Photometry icon  on AIJ's Toolbar. Place the resulting concentric circles onto the target star in the Image Display and left click.
3. This will produce a new Measurements table that should include the SNR measurement under the column Source\_SNR. Each subsequent change in aperture settings and Single Aperture Photometry selections will add a new row to this table.

Note: each such newly created (extraneous) row in the Measurements table should then be deleted before the Measurements table is used for transit modeling. This is done by highlighting the row(s) to be deleted in the Measurements table and then selecting Edit->Cut from the Measurements table menu bar.


Of the above three methods, Method 1 is the preferred one for obtaining an initial set of aperture and annulus settings.

It should be noted that the final settings of the aperture and annulus radii should be those that minimize the Root Mean Square (RMS) of the residuals of the light curve that is created during the transit model fit. RMS is a measure of how well the model “fits” to the observed data. This implies that multiple runs of the model fit, as described in Section 7.11 below, would need to be run with different values for the aperture and annulus radii settings.

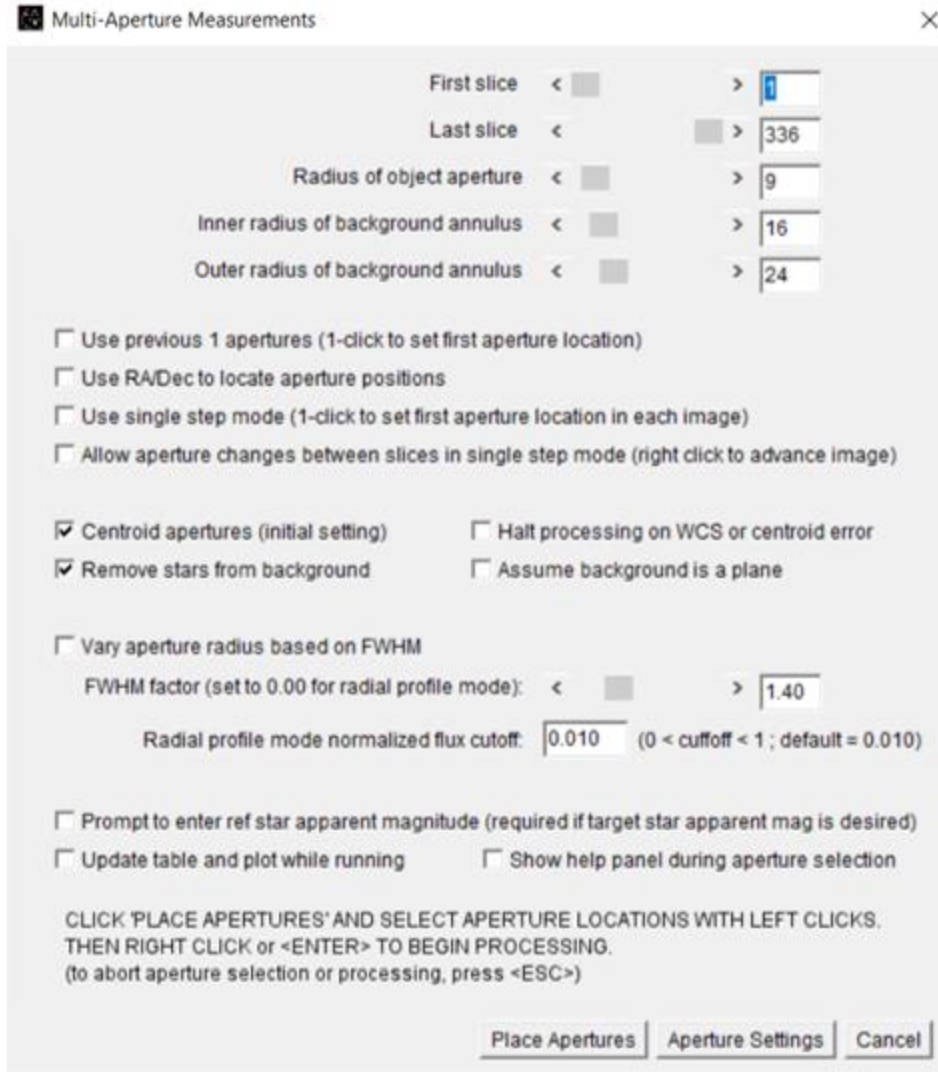
### 7.5.2. Prepare For and Begin the Differential Photometry

In scanning through the images in the stack, it may appear that they are gradually offset from each other and therefore not all aligned. Sections 7.5.3 and 7.5.4 below show how to deal with varying degrees of misalignment, as well as a meridian flip.

On the Aperture Photometry Settings Screen (Figure 11), the user should enter a comma-separated list of keywords for any FITS header values that the user would like extracted and added to the Measurements table. In addition, the appropriate values for the CCD's gain, readout noise and dark current should be entered. Finally, the appropriate settings for Saturation and Linearity warnings should be set. All of the other checkboxes could be kept as shown in Figure 11. The user would then select OK.

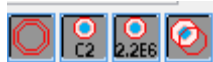
Next, the  icon on the Image Display's menu bar would be selected to bring up the Multi-Aperture Measurements screen (see Figure 13). Values for the range of slices and aperture and annulus radii are automatically filled in. If all the images were plate solved, then “Use RA/Dec to locate aperture positions” could be checked. All other checkboxes could be kept as in Figure 13.





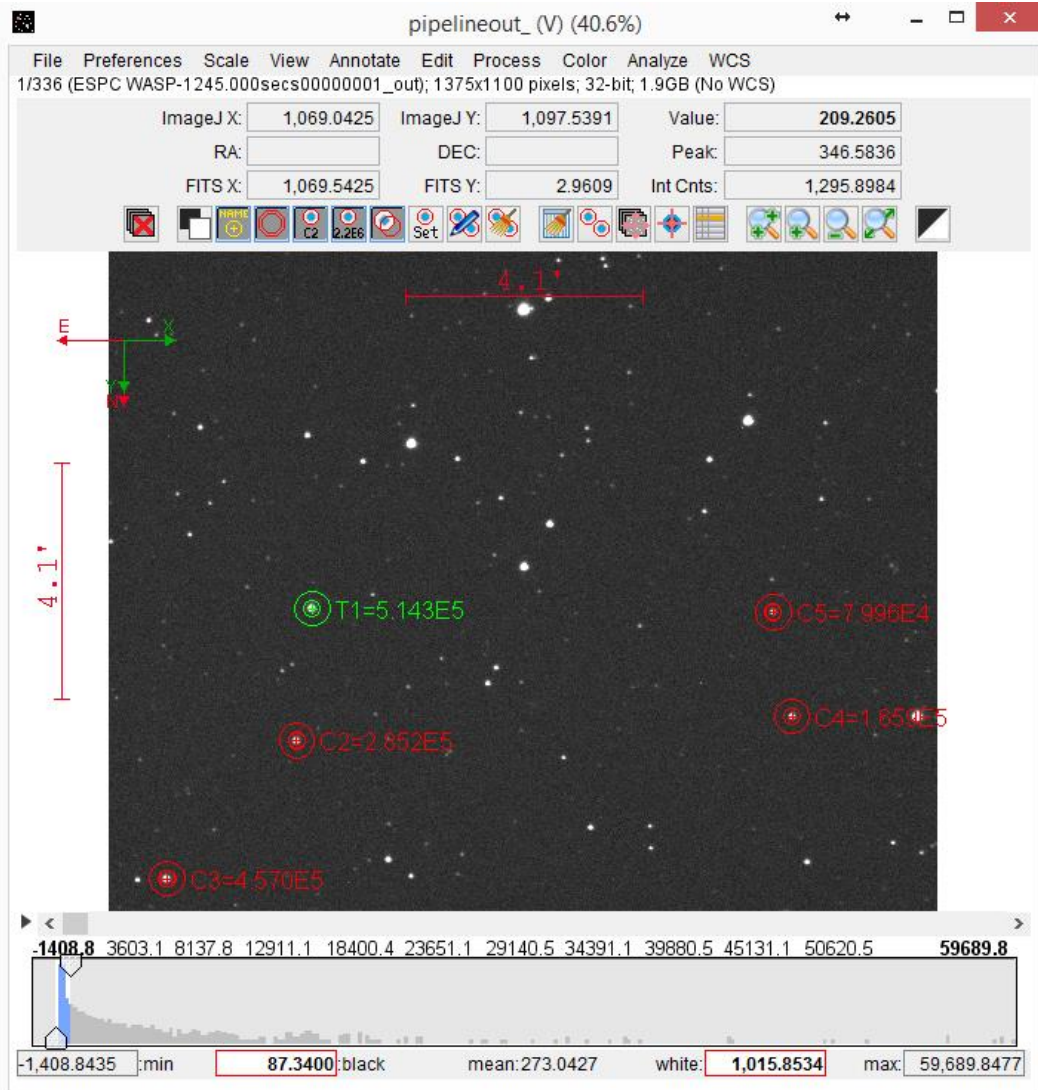
**Figure 13. Multi-Aperture Measurements Screen**

The user should also have enabled the following four icons on the Image Display menu bar:



These selections allow for the aperture/annulus rings to be displayed with target and comp star names and associated intensity counts, and helps to automatically position the aperture/annulus rings on each star's centroid. Note that in a crowded field, it may be appropriate to disable displaying of the annulus rings and intensity counts by deselecting the first and third of the above four icons.

The user would then select Place Apertures and then place and click the floating concentric circles on the target star and the comp stars. The Image Display would then appear similar to that in Figure 14.



**Figure 14. Sample Image with Aperture/Annulus Applied to Target and Comp Stars**

Next, by hitting Enter on the keyboard, the differential photometry process will begin. A Measurements table will be constructed with each row representing the measurements for each slice in the stack. The labels in the Measurements table header identify the type of data in the label's column. Some of these labels correspond to common FITS header identifiers, and others are the Keywords specified in the Aperture Photometry Settings display (see Figure 11).


The following are some of the more important values in the Measurements table that will later be used in the exoplanet analysis (in the notation below, xx =Tn for a star designated as a target and xx=Cn for a star designated as a comparison star):

Source-Sky\_xx – ADU counts within the photometry aperture, adjusted for the sky background counts that are in the photometry annulus;


tot\_C\_cnts – total Source-Sky counts of all the selected comparison stars;  
rel\_flux\_Tx – relative flux of target star Tn = Source-Sky of Tn divided by tot\_C\_cnts;  
rel\_flux\_Cx – relative flux of comparison star Cn = Source-Sky of Cn divided by the  
total Source-Sky counts of all the other selected comparison stars;  
rel\_flux\_err\_xx – error associated with the corresponding relative flux.

At this point, the Measurements table should be saved to a subdirectory like something called AIJ Analysis. This is accomplished by selecting File->Save As on the Measurements table menu and selecting the AIJ Analysis subdirectory. The Measurements table can then be stored by AIJ with an extension of .xls, .tbl, or .txt. The extension to be used for the Measurements table can be set by going to the main AIJ menu bar and selecting: Edit->Options->Input/Output and entering the desired extension in the “File extension for tables” box. Note: it is preferable that an extension of .tbl be used for the Measurements table.

It should be noted that if the differential photometry needs to be redone on images currently in the stack, the following steps should be done:

1. Clear the existing aperture/annulus rings by selecting the “clear apertures and annotations from overlay” icon  on the Image Display.
2. On the Multi-Aperture Measurements Screen (Figure 13), make sure that the checkbox next to “Use previous X apertures” is unchecked.

### 7.5.3. Dealing with Misaligned Images

A shift in image orientation and therefore misalignment could be the case if guiding is poor. If the image shift is not too severe, AIJ’s Align Stack function could be used to align the images in the active stack. This can be accomplished by selecting the “align stack using apertures” icon  on the Image Display screen and entering a fairly large aperture setting, with correspondingly larger annulus settings. Images in the stack are aligned using this feature and the resulting aligned images are stored in a new subdirectory labelled “aligned.” Images in this subdirectory should then be the ones used during the differential photometry phase. The user should not forget to change back the aperture and annulus settings to ones that are appropriate for the differential photometry phase.

In the case of image rotation due to severe image shift, which AIJ’s Align function cannot correct, then the following can be done:

1. First, plate solve each image (see Section 7.4).
2. After plate solving has been completed, the user can then perform the differential photometry as before, except that on the Multi-Aperture Measurements screen (Figure 13), the box labelled “Use RA/Dec to locate aperture positions” should be checked. In addition, the First and Last slice should indicate the entire range of slices.
3. When the Place Apertures button is selected on this screen, the user would then place the aperture/annulus rings on the target and comp stars and, as before, press Enter on the

keyboard. All the images in the stack are now analyzed.

#### 7.5.4. Dealing with a Meridian Flip

If a meridian flip had occurred during the imaging session, then the images would be rotated 180° from the orientation shown in Figure 5. Thus, for the images taken after the flip, the aperture/annulus rings would not fall on the correct locations for the target and comp stars. Note: even if the CCD camera itself was rotated immediately prior to the beginning of imaging after the meridian flip, it is unlikely that the target and comp stars would land within the same aperture/annulus rings.

To conduct differential photometry with AIJ in the case of a meridian flip, the following method can be used (note: if there are misaligned images during the pre-flip period or during the post-flip period, then the method described in Section 7.5.3 should be used):

1. First, plate solve just the first image in the entire sequence. This is accomplished by entering “1” in both the Start Slice and End Slice fields of the Astrometry Settings screen. This will cause just the first image in the stack to be plate solved.
2. Next, the slice number for the image in the stack immediately following the meridian flip should be entered in these two fields and it should be plate solved.
3. On the Multi-Aperture Measurements screen (see Figure 13), the checkbox labelled “Use RA/Dec to locate aperture positions” should then be CHECKED and the checkbox labelled “Halt processing on WCS or centroid error” should be UNCHECKED.

When the differential photometry is now conducted, AIJ will proceed through the pre-flip images, using the coordinates in the first slice for placement of the aperture and annulus on subsequent pre-flip images, and then using the coordinates of the first slice after the flip for the remaining images in the stack.

#### 7.5.5. Storing and Later Retrieving Target and Comparison Star Locations


It is sometimes desirable to store, and then at some later time retrieve, the location of the user’s target and comparison star selections. AIJ provides this capability as follows.

1. Before the differential photometry process begins, at least the first image in the stack should be plate solved.
2. On the Multi-Aperture Measurements screen, the “RA/Dec to locate aperture positions” entry should be selected, and the “Use previous x apertures...” and “Halt processing on WCS or centroid error” entries should NOT be selected.
3. Next, the user should place apertures on the target and the desired comparison stars and then press Enter to conduct the differential photometry on all the images.
4. Once the Measurements table is created, from the Image Display the user should then select File->Export apertures to RA/Dec list... and then store the resulting file of target and comparison star locations in the AIJ Analysis directory.

If the user then wishes to use this same selection of target and comparison stars at a later time, the following process would be followed:

1. On the Multi-Aperture Measurements screen, the “Use previous x apertures...” entry should be selected, as well as the “RA/Dec to location aperture positions” entry.
2. On the Image Display, the user would then select File->Import apertures from RA/Dec list... and choose the previously stored file of target and comparison star locations. The target and comparison stars selections would then turn light green and red, respectively.
3. Next, on the Multi-Aperture Measurements screen, the user would select the Place Apertures tab.
4. The target and comparison star selections would then turn brighter green and red, respectively.
5. The user would then hit Enter to begin the differential photometry process as usual.

#### 7.6. Prepare for Model Fit

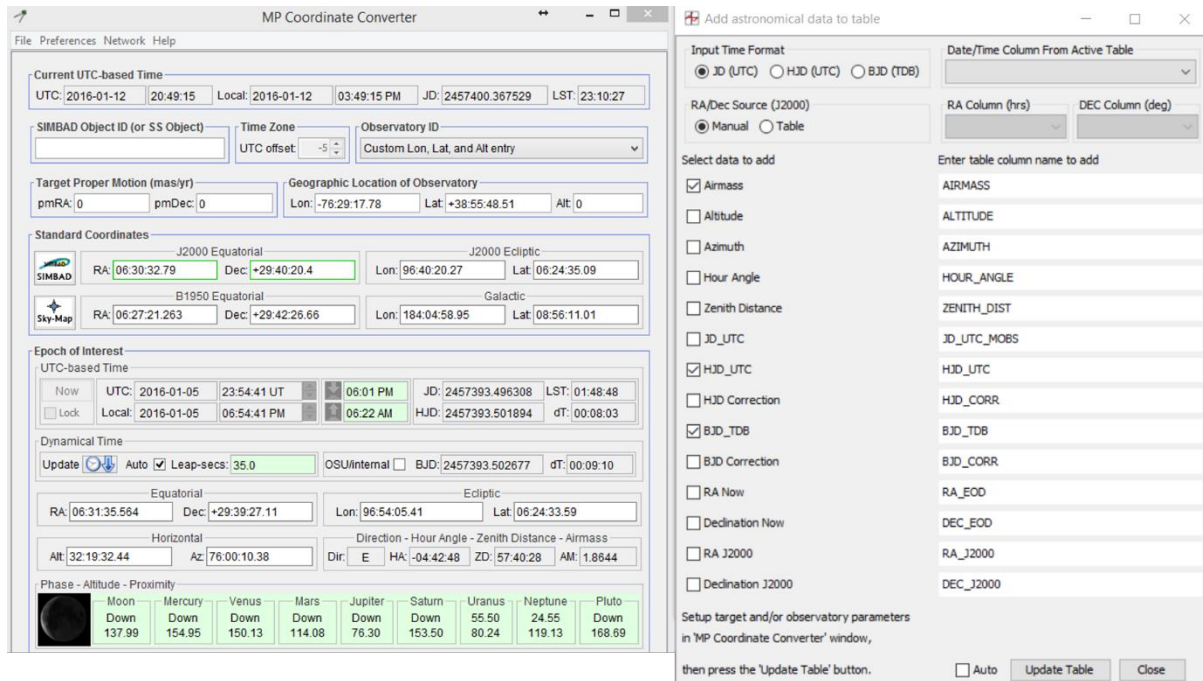
In preparation for a model fit, the Multi-Plot Main  icon on the AIJ toolbar should be selected. When this is done, the following four screens pop-up:

Multi-plot Main  
Multi-plot Reference Star Settings  
Multi-plot Y-data  
Data Set 2 Fit Settings.

An AIJ file with an extension of .plotcfg contains the information used to create these screens. A template.plotcfg file that the user can start with can be found at <http://astrodennis.com>. The user can open a .plotcfg file by going to the upper left corner of the Multi-plot Main screen and selecting “File->Open plot configuration from file...” Likewise, the current instance of the above screens can be stored by selecting “File->Save plot configuration...”

The first step is to update correct values in the AIRMASS, HJD.UTC, and BJD.TDB column entries in the Measurements table if this was not done during the Calibration phase (see Section 7.2 above). This is accomplished as follows:

From the Multi-plot Main menu, select “Table->Add new astronomical data columns to table.” The following two screens then appear: “MP Coordinate Converter” and “Add astronomical data to table” (see Figure 15).




**Figure 15. Screens for Correcting AIRMASS and Time Standard Values**

On the MP Coordinate Converter screen, verify that the values are correct for Geographic Location of Observatory and the J2000 Equatorial Coordinates for the target star. Also, select Auto under the Dynamical Time section. On the “Add astronomical data to table” screen, verify that the boxes are checked as shown in the right-most screen in Figure 15, and then select Update Table. Press OK if the “Over-write existing data?” dialog box appears. The AIRMASS, HJD\_UTC, and BJD\_TDB columns in the Measurements table will then be updated.


### 7.7. Conduct Model Fit

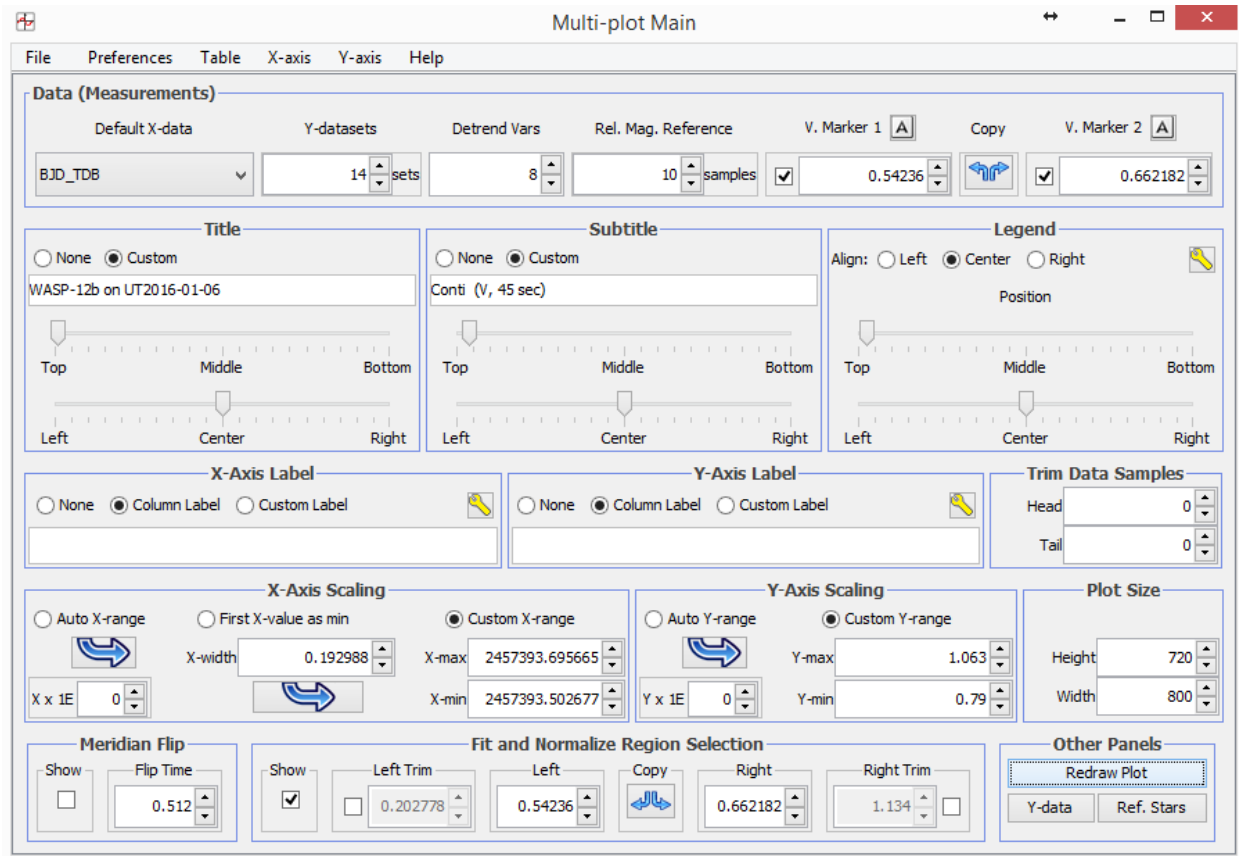
On the Multi-plot Main screen, the default X-data (namely the timeframe to be used) should be selected. In the example shown in Figure 16, because values for the (preferred) timeframe of BJD\_TDB have been included in the Measurements table, BJD\_TDB is selected. Appropriate entries for Title and Subtitle are also made.

Also on the Multi-plot Main screen, under the Fit and Normalize Region Selection box, entries are made for the Left and Right boxes that represent the predicted transit start and end times, respectively. At the upper right of the Multi-plot Main screen, the copy icon  is then selected. This positions the Predicted Ingress and Predicted Egress times on the V.markers at the appropriate places on the Plot of Measurements screen. The V.markers should remain untouched thereafter in order to show what the initial predictions were. However, the Fit and Normalize markers should later be positioned to the apparent ingress and egress points as shown on the Plot of Measurements screen (Figure 22). The Fit and Normalize markers are used by AIJ to define

the out-of-transit data that is used to compute a baseline that the model fit uses to compute the relative normalized flux across the entire observation.

The Left Trim and Right Trim fields can be used to eliminate some amount of pre-ingress and post-egress data from the model. This might be done, for example, if there were systematics during the beginning or end of the observing session. The values in the Meridian Flip, Fit and Normalize Region, and V.Marker boxes are only the decimal part of the associated time (for example, 0.83508 would be entered if the time in question was 2457395.83508). If, however, the begin time is, say, 2457395.83508 and the end time “rolls over” into, say, 2457396.00175, then the begin decimal part should be 0.83508, but the end decimal part should be 1.00175.

Next, under the X-Axis Scaling box, check the Auto X-range button and click on the  icon. The X-min and X-max boxes will automatically be filled in with the minimum and maximum X values (BJD\_TDB times in this example) that are in the Measurements table. Note: for this to work, at least one row on the Multi-plot Y screen (see Figure 17) should have its checkbox checked in the Plot column. Alternatively, the user can click on the Custom X-range box and fill in different X-min and X-max values. The Y-Axis Scaling box can be used now or later to allow the various plots to be sized so they all appear on the Plot of Measurements screen (see Figure 22). The Plot Size entries are used to size the Plot of Measurements screen on the user’s computer monitor.

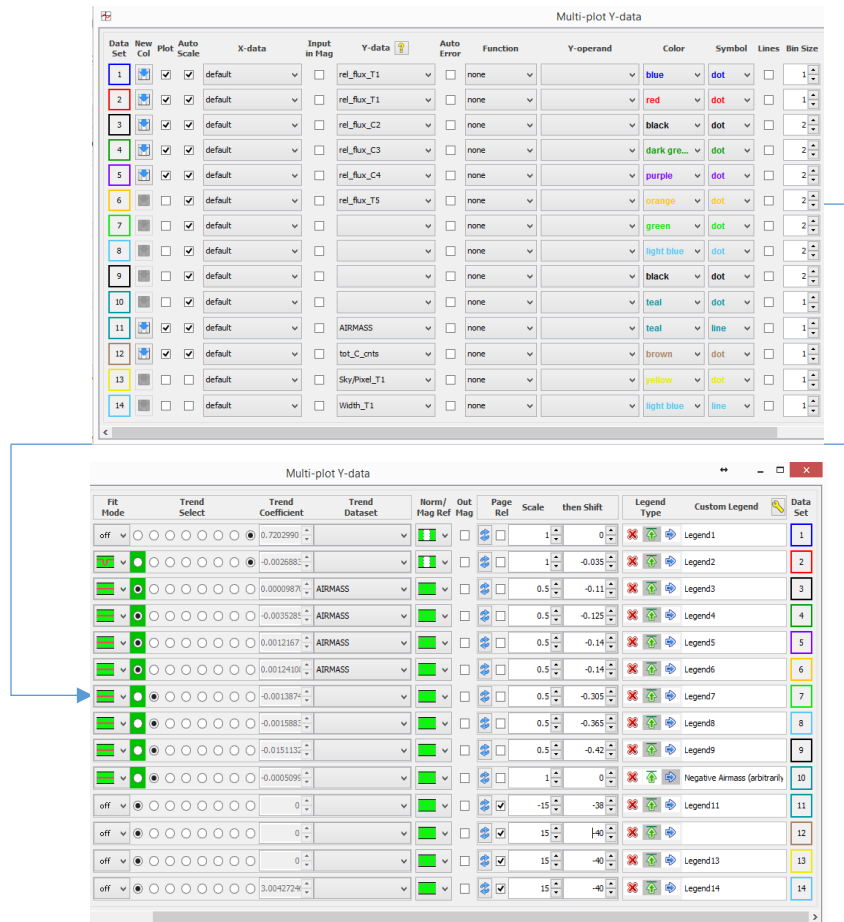


**Figure 16. Multi-plot Main Screen**

If a meridian flip has occurred, or if there is a break in the image session and the stars have moved to a different part of the CCD detector, then the Meridian Flip box on the Multi-plot Main screen is used to place a line in the middle of the gap where this discontinuity of data has occurred. The Show box should be checked and an entry made in the Flip Time box so that the Meridian Flip line is placed on the Plot of Measurements screen at the appropriate place.

## 7.8. Light Curve Plot

Before a visual plot of selected data sets can be obtained via the Plot of Measurements screen (Figure 22), the Multi-plot Y Data screen (Figure 17) needs to be setup. This is the main screen that determines where and how different data sets are plotted



**Figure 17. Multi-plot Y Data Screen**

The following are the key parameters and selections for the Multi-plot Y screen:



The Plot column is used to select if a particular data set is to be plotted.

For each particular data set, the X-data column indicates what values from the Measurements table are used on the X-axis. A selection of “default” equates to the default values specified on the Multi-plot Main screen; in the example used throughout here, BJD\_TDB is the default. The Y-data column is used to select which columns in the Measurements table are used for the Y-axis values.

The Bin Size column indicates the number of points in the associated data set that are combined (binned) into one point. Note that “binning” here is different from the concept of binning used when, for example, CCD photosites are binned together. Note that binning is for display purposes only and does not change the underlying Measurements table data, unless the user adds additional columns containing binned data as described in Section 7.12.

The Fit Mode column is used to select the type of fit that should be applied to the respective data set, as well as the span of data (indicated by the green area) that will be included in the fit. Thus, as seen in Figure 22, the raw data points of the relative change in flux of T1 are plotted with no fit, while the second plot is a fit of this same data using an assumed transit model. Also as seen in this example, the relative flux changes of three comp stars are fit with a straight-line model (as will be seen later, one of the original comp stars, C5, was deselected after it was found to have significant residual errors). The reason for the latter three plots being linear is because it is assumed that there should be no relative changes in the comp star brightness throughout the imaging session, unlike the relative flux of T1 where it is assumed that it will reflect a dip in brightness due to the exoplanet’s transit.

The Trend Select column serves two purposes. First, it reflects the detrend parameters that are being applied to the associated Fit Mode, which themselves will be selected on the Data Set 2 Fit Settings Screen (Figure 18). Active detrend parameters are indicated by green. Second, selecting a particular detrend parameter will reflect its Trend Coefficient and the associated type of detrend data (e.g., AIRMASS).

The Norm/Mag Ref column indicates the range of data used to normalize the respective data set. In the example in Figure 17, the relative flux of T1 is normalized based on the out-of-transit data – i.e., data to the left of the begin-of-transit (ingress point) and to the right of the end-of-transit (egress point). As discussed earlier, these latter two points are set by the values in the Fit and Normalized Region Selection boxes on the Multi-plot Main Screen (Figure 16).

When checked, the Page Rel column indicates that the Scale and Shift columns should be interpreted as the percentage of the Y-range. Unchecked means that the Scale and Shift values are absolute numbers applied to the Y-range. The Scale and Shift values, along with the Y-min and Y-max values on the Multi-plot Main screen, are used to properly position the various plots on the Plots of Measurements screen. It should be noted that the raw data set representing the relative flux of T1 (namely the first row in Figure 17)

should always have a Scale value = 1. This is because this data may be used by other global fit programs and should not be scaled.

## 7.9. Data Set Fittings Screen

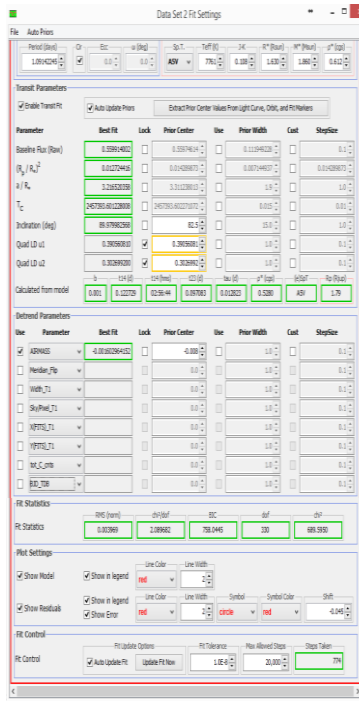
The Data Set 2 Fit Settings Screen (Figure 18) is automatically opened whenever there is a Transit Fit selected for a data set (in this case Data Set 2) under Fit Mode on the Multi-plot Y Data screen (Figure 17). The following user inputs on the Data Set 2 Fittings Set Screen are made that affect the resulting light curve:

Period – the orbital period, if it is available, from <http://exoplanets.org/>; for example, in the case of WASP-12b, it is 1.09142245 days.

Host Star Parameters – the spectral type (Sp.T) of the host star; this is strictly to estimate the radius  $R_*$  of the host star, which itself is used simply to calculate the radius of the exoplanet. If the user has knowledge of  $R_*$  (for example, from <http://exoplanets.org/>) then this value may be entered in the  $R_*(R_{\text{sun}})$  box. In this example for WASP-12,  $R_*=1.630$ .

Quad LD U1 and Quad LD U2 – these are the quadratic limb darkening coefficients associated with the host star and the particular filter being used. These values can be found by using the limb darkening coefficient calculator at <http://astrutils.astronomy.ohio-state.edu/exofast/limbdark.shtml>. In the example here, the coefficients used for WASP-12b are 0.39056081 and 0.3026992, respectively. Note that these are placed in the Prior Center Column and locked.

The AIRMASS Prior Center value should be set to 0.0 in most cases.



**Figure 18. Data Set 2 Fit Settings Screen**

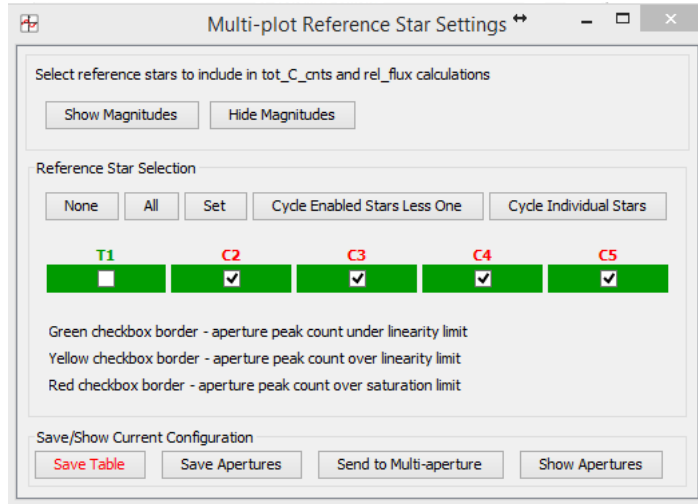
The Y-min and Y-max values on the Multi-plot Main screen can be adjusted to display desired portions of the Measurements table on the plot, although as previously mentioned, it is best to select Auto-X-range under X-Axis Scaling on the Multi-plot Main screen to display the entire range of X-values.

It is possible to see how the fit is improved by applying any number of Detrend Parameters. The most common is AIRMASS. Other Detrend Parameters can also be selected. If a meridian flip or a break in data collection has occurred where stars have moved on the CCD detector, then Meridian\_Flip can also be selected (note that if this is done, the Flip Time selection and value must be made on the Multi-plot Main screen). Other Detrend Parameters could also be selected to see their effect(s) on the model fit. A good rule of thumb for whether a Detrend Parameter is effective is to view the Bayesian Information Criterion (BIC) value. If it reduces by more than 3.0 when a Detrend Parameter is selected, then that Detrend Parameter should be selected. If it decreases by less than 3.0 or increases, then the Detrend Parameter is not that relevant. See Section 7.11 for a more detailed discussion on selecting detrend parameters.

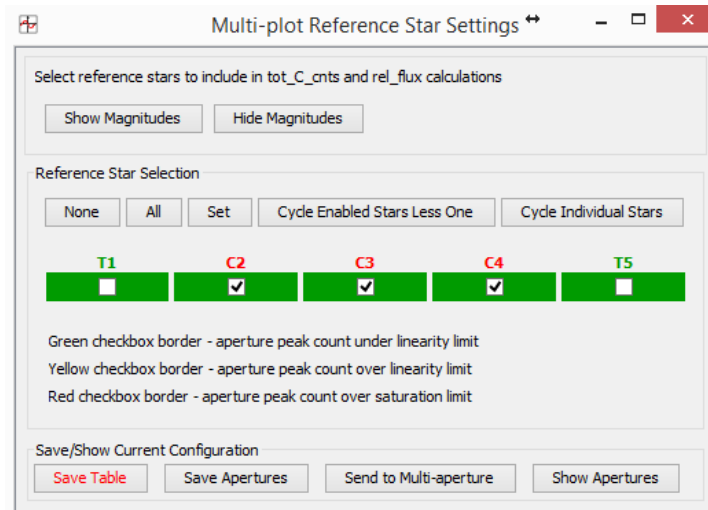
Plot Settings on the Data Set 2 Fit Setting Screen are used to define if and how the transit model and residuals are displayed. In addition, a Shift value is used to move the residual plot up or down on the Plot of Measurements screen.

Finally, the Multi-plot Reference Star Settings screen (Figure 19) is used to deselect or select which comp stars the user would like to include in the model fit. This is useful if it is determined after viewing a particular comp star's relative flux in the Plot of Measurements screen (Figure 22) that its data points do not follow a linear fit – i.e., an indication that it is most likely a

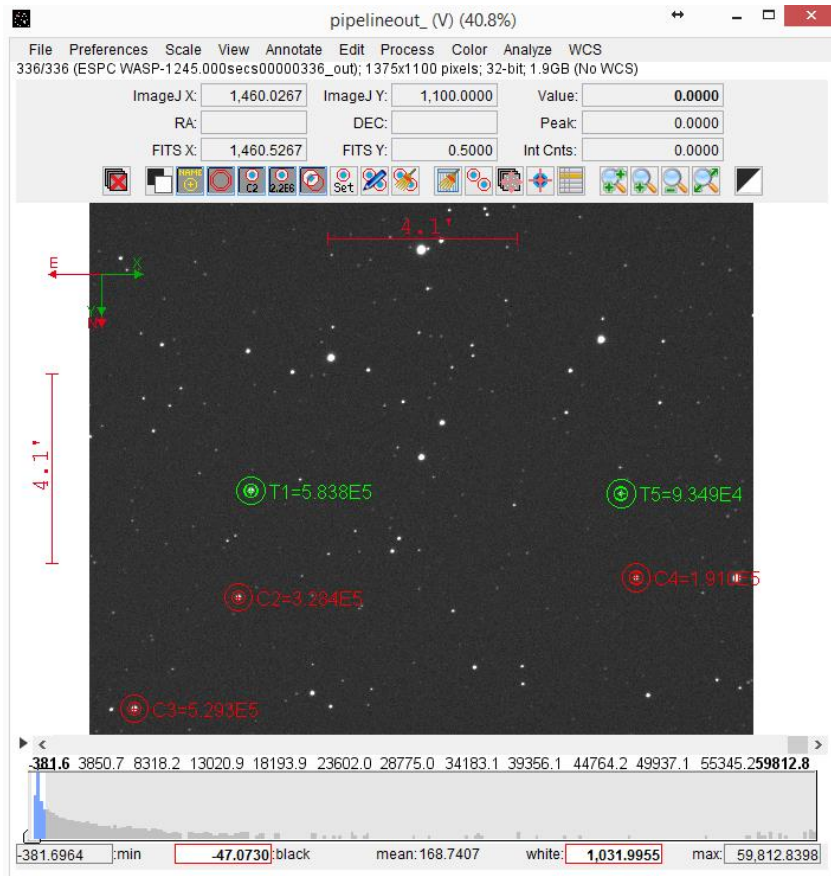
variable star. In the example here, it was determined that comp star C5 had a large number of residual errors. Thus, it was deselected from the ensemble of comp stars to be used (see Figure 20). When this deselection took place, comp star C5's identifier was changed to T5 both on the screen depicted in Figure 20, as well as on the Image Display (see Figure 21). Its Plot selection box in Figure 17 was then unchecked so its plot no longer appeared in Figure 22.



**Figure 19. Multi-plot Reference Star Settings Screen**



**Figure 20. Multi-plot Reference Star Settings Screen after C5 was Deselected**



**Figure 21. Updated Images Display Showing C5 Changed to T5**

Note that C5's data is now not included in the model fit, but its data is still maintained in the Measurements table.

The settings in Figure 16, Figure 17, Figure 18, and Figure 20 produced the light curve and other plots shown in Figure 22.

Figure 23 is an example of an exoplanet fit based on data collected by amateur astronomer Paul Benni for exoplanet Wasp-76b. It shows how a Meridian\_Flip detrend parameter was used to take care of an offset in data points caused by the target and comp stars landing on a different part of the CCD detector after the meridian flip occurred.

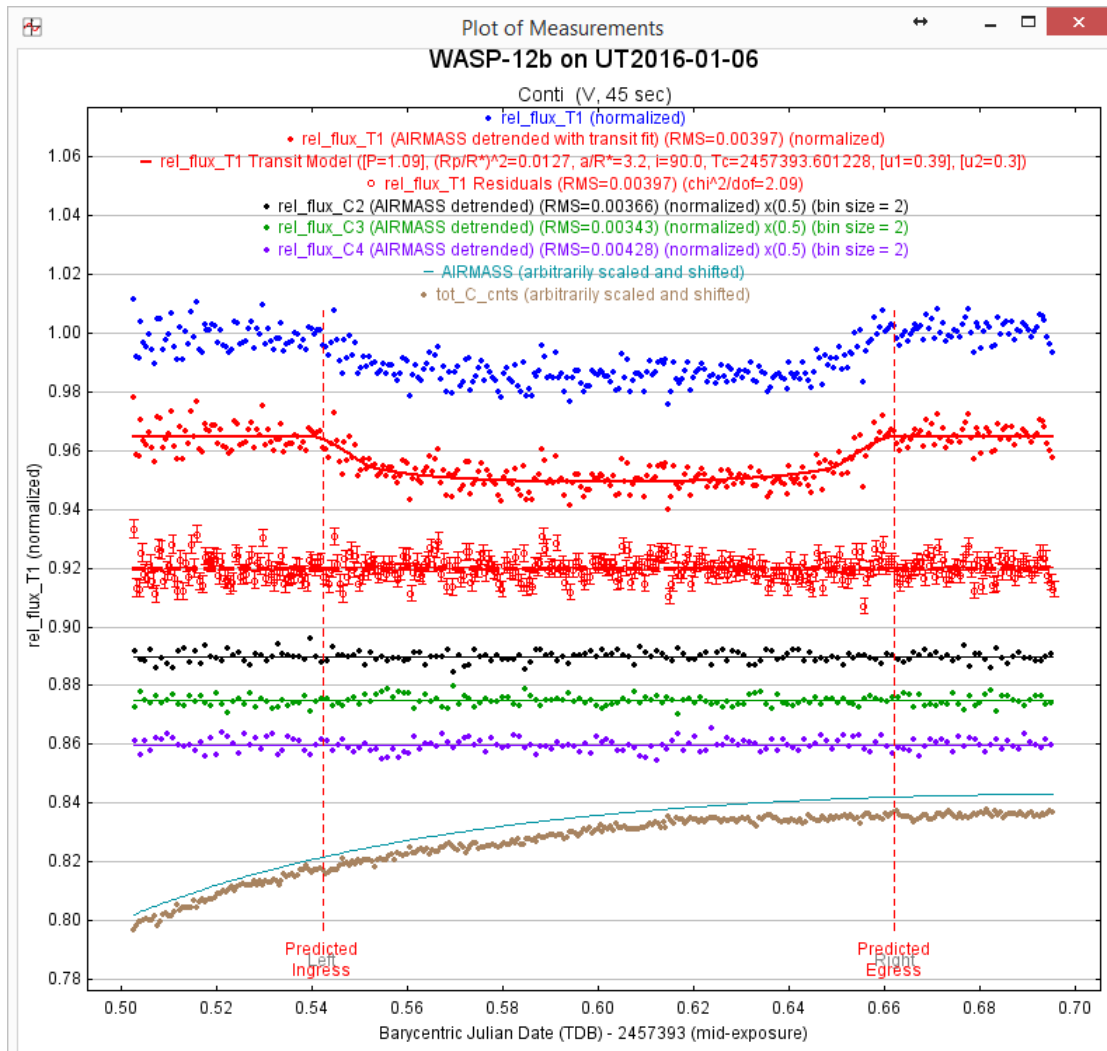


Figure 22. Plot of Measurements Screen