Observing Guide to Transiting Extrasolar Planets

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Abstract

1. Transiting Extra Solar Planets inventory

The census of ESP in the solar neighborhood started 20 years ago, and at the moment of writing around 300 planets are known. Most of them are orbiting around G and K dwarves or slightly evolved, and only a small number around M dwarfs. It is important to remind that this sample is not representative of the true ESP population in the Galaxy, because actually ESP survey are mainly focused on solar type stars.

The resulting population of ESP is composed by planets with masses between few Earth masses and 20 Jupiter masses, with orbital periods ranging from 1 day to about 15 years, and orbital eccentricity between 0 and 0.996. About one sixth of the known ESP during their orbit pass on the front of the stellar disk, producing a partial occultation of the star, that is usually named transit, from the analogous phenomenon of the inner planet of Solar System. Transiting planets can be assimilated to eclipsing binary and using the same methodologies used for studying these objects it is possible to determine the planet and star radii. The measured radii of the planets ranges from few Earth radii to about 2 Jupiter radii. Some planets have radii anomalously larger than the expected value from theoretical speculations, this could be due to tidal heating or to the strong stellar irradiation that inflate the planet radius.

2. Duration of the observations

Transits of extrasolar planets have a typical duration of 3 hours, this value depends on the orbital period, the planet and star radii. In order to obtain a lightcurve useful for a scientific analysis it is necessary to have a long time series before and after the transit. The Out Of Transit (OOT) part of a lightcurve permit to estimate the value of depth of transit and to correct for the presence of systematics (e.g. reference stars with colors very different from the target star). A practical rule for the observations of a transit is to obtain at least data from one hour before the transit up to one hour after the transit.

The duration of a planetary transit can be obtained with the formula due to Tingley & Sackett (2005). The formula is accurate to few percent for the very eccentric orbits (e > 0.8).

\[ D = \frac{2(R_s + R_p) r_i}{\sqrt{G(M_s + M_p) i (1 - e^2)}} \sqrt{1 - \frac{r_i^2 \cos^2 i}{(R_s + R_p)^2}} \]  
(1)

where \( R_s \) is the star radius, \( R_p \) is the planet radius, \( M_s \) is the star mass, \( R_p \) is the planet mass, \( G \) is the gravitational constant, \( a \)

\[ r_i = \frac{a(1 - e^2)}{1 + e \cos(\pi/2 - \omega)} \]  
(2)

\( \omega \) is argument of periaphron of the planet.

Depth of transit in flux units

\[ \frac{dL}{L} = \left( \frac{R_p}{R_s} \right)^2 \]  
(3)

Depth of transit in magnitudes

\[ \delta M = -2.5 \log_{10} \left( 1 - \left( \frac{R_p}{R_s} \right)^2 \right) \]  
(4)

Se il raggio della stella è noto (per esempio dalla classificazione spettrale), dall’equazione (??) si può ricavare \( r_p \), se sono noti anche il periodo orbitale \( P \) e la massa della stella \( M_s \), si può ricavare il semiasse maggiore orbitale \( a \) dalla terza legge di Keplero, e quindi si può infine ricavare la durata del transito (?):

\[ \tau = \frac{P}{\pi} \left( \frac{R_s \cos \delta + r_p}{a} \right) \leq \frac{PR_s}{\pi a} \]  
(5)

dove \( \delta \) è la latitudine del transito sul disco stellare. La durata del transito di Giove e della Terra per \( a \cos i = 0^\circ \) (transito equatoriale) vale rispettivamente 25 h e 13 h. Dall’equazione precedente si può ricavare \( \delta \), e quindi l’inclinazione dalla:

\[ \cos i = \frac{R_* \sin \delta}{a} \]  
(6)
Conseguentemente la minima inclinazione a cui avviene il transito è ($\delta = 0$):

$$i_{\text{min}} = a \cos \frac{R_*}{a}$$

(7)

La probabilità geometrica di osservare un transito con inclinazione casuale è:

$$p = \frac{R_*}{a} = \cos i_{\text{min}}$$

(8)

Una valutazione di $i$ e $p$ per casi reali mostra che $i$ è molto prossimo a $90^\circ$ e $p$ è molto piccolo (nel caso di Giove e della Terra vale rispettivamente 0.001 e 0.05), quindi i pianeti che risiedono in orbite di breve periodo sono maggiormente favoriti per effettuare un transito sul disco stellare.

Probabilità di occorrenza di un transito in funzione dei parametri orbitali del pianeta noti dalle velocità radiali:

$$P_T = 0.0045 \left(\frac{1 \text{AU}}{a}\right) \left(\frac{R_* + R_p}{R_\odot}\right) \left[1 + e \cos\left(\frac{\pi}{2} - \varepsilon\right)\right]$$

(9)

Equazione delle effemeridi

$$T_c = T_{0\circ} + NP$$

(10)

$T_c$ tempo della centralità del transito in HJD, $T_{0\circ}$ tempo della centralità del primo transito in HJD, $N$ numero di transiti trascorsi dal primo transito, $P$ periodo orbitale in giorni.

Errore sulle effemeridi

$$\sigma_{T_c} = \sqrt{N^2 \sigma_P^2 + \sigma_T^2}$$

(11)

$$\sigma_P$$ errore sul tempo della centralità del transito in HJD, $\sigma_T$ errore sul tempo della centralità del primo transito in HJD, $N$ numero di transiti trascorsi dal primo transito, $\sigma_P$ errore sul periodo orbitale in giorni.

Densità di un pianeta, assumendo che sia una sfera di densità costante

$$\rho = \frac{3 M_p}{4\pi R_p^3}$$

(12)

Calcolo dell’istante della centralità del transito $T_c$ a partire dalla conoscenza del momento del passaggio al periastrro $T_0$

$$T_c = T_0 + \frac{P(E - e \sin E)}{2\pi}$$

(13)

dove $P$ è il periodo orbitale, $e$ è l’eccentricità orbitale, $E$ è l’anomalia eccentrica al momento del passaggio al periastrro calcolabile risolvendo l’equazione di Keplero.

3. Telescope requirements

Minimum telescope diameter for obtaining useful data from the observations is 8 cm = 3.15 in. Given that the photometry performed on bright stars will require out of focus images, the requirements on the optical quality of the mirror surfaces are moderate, with $\lambda/4$ being sufficient.

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4. Filters

Images must be taken with the most red filter that is available. To break down the problems of extinction in the field, the best choice would be a I filter. At these wavelengths back illuminated CCD chip could suffer of the fringing effect, it is not easy to deal with this problem. For omogeneity in lightcurves obtained it is suggested to observe only with R filters with any kind of CCDs (back or front illuminated), using an R filter we can combine light curves more easily. It is not required that the filter is photometric filter, but it is necessary that the filter cuts the blue wavelengths that are those largely concerned by the scintillation.

If you don’t have any R filter you can use efficiently V or I filters. In Table 1 is presented a list of filter vendors and their suitable filters for transits observations.

The use of narrow band filter do not help in the observations of transits. The main purpose of these observations is to obtain the largest number of photons. With narrow band filters the number of photons received by unit time is lower than in a wide band filter. These filters may have also the characteristic of being sensitive to certain emission lines in the stellar spectra stars, lines that could be not present in the target star. Comparison of fluxes obtained in these particular regime could be problematic because the measure will be very sensitive to changes in the background and/or weather conditions.

5. CCD

If you have a CCD equipped with anti-blooming, a color CCD, or a CMOS detector it is necessary to verify the linearity response of the detector before to plan any transit observations.

The exposure time must be as long as possible to break down the scintillation, trying not exceed the 80% the value of saturation value for the most brightest star in the field and at the same time to fall below 60%. The eernal rules for the observations are:

- during observation the autoguide and cooling must always be turned on
- work only in the regime of linear response of the camera
- use only binning 1×1

The frequent question is why not use a 2×2 binning or greater.

Table 1. Notes: 1) Bessel photometric system [Bessell, 1990]; 2) Bessel photometric system [Bessell, 1990] plus Z filter 3) G ≈ short V Bessel, R ≈ DSS1; 4) G ≈ short V Bessel, R ≈ Sloan; 5) G ≈ short V Bessel, R ≈ Sloan, IR could be ProPlanet IR 742 CCD or ProPlanet IR 807 CCD; 6) G ≈ short V Bessel, Orange(O) and Red(R) are Warratts filters; 7) Warratts filters, green filters are band pass filters while red and infrared are high-pass filters; 7) a useful link on Schott filters is http://www.optical-filters.com/schott.html
The advantages to use this type of binning compared to 1×1 binning are: the decrease the readout (that is already low) and the decrease the RON (is already low because we are working at high count level).

On the other side we have disadvantages: as first point there is lack of uniformity in the way of doing the binning in the various chips and possible loss of accuracy in the conversion to 16-bit (different implementation by manufacturers of chips). Second the shorter exposure times increase the scintillation. Third there is a greater sensibility to hot/dead/cosmic pixel, if one pixel is hot/dead/cosmic, all the binned pixel suffer from this one. And finally with the same defocus the number of pixel for the photometry decrease, as a consequence the photometric precision is lower and the Signal to Noise Ratio (SNR) decrease.

5.1. Linearity test

Ideally the signal that is read out from the CCD will depend linearly on the flux of photons. In other words, a short and a long exposure should give the same number of photons per second. At some level all CCDs suffer from nonlinearities, at least when the count level is close to the saturation limit of the CCD. . . .

6. Calibration images

6.1. Flat fields

The flat fields should be obtained at the beginning or at the end of the observing session. They can be obtained on the sky after the sunset or before sunrise (named sky flats) or using a "flat box" (named dome flats), or directly from your science images (super sky flats, a median of many science frames). Dome flats are inferior to sky flats. Only when flat (dome or sky) images are not available you can obtain the super sky flat flat directly from the science images using the method of Kuhn et al. (1991). This method is currently implemented in IRIS. Super sky flat was demonstrated to be superior to sky flats when crowding of the fields is not very important (Alcala et al., 2002).

For obtaining a sky flat you need to point the telescope to a blank field, a suitable list is reported in Tab. 2.

6.2. Dark frames

You should take dark frames always with the same exposure time as the images from which you want to subtract them. If you scale them to a different exposure time, then you also scale the readout noise, which is independent on the exposure time. Besides, even though they are small, non-linearities exist in the images.

The CCD camera must be thermostated. If not you need to accurately control the temperature of the CCD by eye, and obtain a series of 3 dark frames at every change in temperature greater than 0.5 °C. This means to interrupt the science sequence, obtain the dark images and restart the sequence. The typical time between two dark sequence is 30 minutes.

However, note that the bias and dark is usually not stable. Because you require dark subtraction, take the darks as close as possible to your observations.

6.3. Bias frames

Bias frame must be obtained. If your camera does not have an obturater, but your CCD chip contain overscan region you can
determine the bias level calculating the median values of these regions.

6.4. Meridian flip and calibration frames

For who has German mount it will be necessary to reverse the telescope on the passage of the meridian. In this situation it is necessary to obtain flat fields in the two configuration. Experience show that data reduced with flat field obtained in only one of the two configuration cannot be used to identify tran-
sits.

7. How to photometer bright stars: the defocus technique

Bright stars saturate very rapidly the CCD pixels. To avoid this problem it is necessary to defocus the telescope in order to put the incoming stellar light on many pixels. This can be performed with a microlens-array.

7.1. Defocus to be revised

The defocus permit a larger number of detected star photons to be accumulated in each exposure without saturating the CCD and also reduce systematic errors related to flat fielding and image motion.

When the object and image-receiving surface are not conjugate there is defocus or in other terms defocus image is out-of-focus if receiving plane is not at the image focus.

By geometry (Fig. 2) we have:

\[
D = \frac{d}{\Delta f} \tag{14}
\]

\[
\Delta = \frac{2df}{D} \tag{15}
\]
For a given blur circle diameter (as specified in a design, for example), the depth of focus is proportional to \( f/D \).

### 7.2. Microlens array

... 

### 8. Exposure time

#### 8.1. On focus images

The exposure time for a given SNR is:

\[
t_{\text{exp}} = \frac{-b + \sqrt{b^2 - 4ac}}{2a}
\]

where:

- \( a = N^2 \)
- \( b = -SNR^2(N + n_{\text{pix}}(N_S + N_D)) \)

...
8.2. Defocused images

Defocused images can be considered as extended images. Defocus radii and exposure time are directly related, fixing one the other is univocally determined.

\[ r = \sqrt{\frac{N \cdot g \cdot t_{exp}}{\pi \cdot P \cdot FWC0}} \]  
\[ t_{exp} = \frac{\pi \cdot P \cdot FWC0 \cdot r^2}{N \cdot g} \]

(21)
(22)

The radius of the defocus star in arcsecond is the radius in pixel multiplied by the telescope scale The scale of the telescope in "/px is:

\[ s = \frac{206.265 \cdot px}{f} \]  
\[ \text{with px expressed in } \mu m \text{ and } f \text{ in mm.} \]

9. Scintillation

Dravins et al. [1998] provided a formula for calculating the approximate contribute of the scintillation to the photometrical errors in terms of relative flux \((dL/L)\):

\[ \sigma_{\text{scint}} = \frac{0.09d^{2/3}A^{1/2}}{2^{1/3}t_{\text{exp}}^{2/3}} \]  
\[ \text{where } d \text{ is the telescope diameter in centimeters, } A \text{ is the air-} \]

mass, \(h\) is the height over sea level in meters, \(t_{\text{exp}}\) is the exposure time in seconds.

In Tab. 5 is reported in the scintillation expected for typical diameters and exposure times. To obtain the best possible lightcurve is necessary to minimise the contribution of scintillation. As the scintillation is dominant noise source for telescopes with diameters less than 40 cm = 15.75 in, the best solution for decreasing this contribution is to have long exposure times. With long exposure times the "high" frequency contribution of the scintillation will be averaged. For faint stars, \(V > 10\), long exposure times are already necessary due to the low number of photons that reach the telescope. On the other side, for very bright stars, for obtaining long exposure time it is necessary to strongly defocus the star. In this case exposure time must be long enough to have a maximum value for the scintillation equal to 0.002.

Formula della massa d'aria

\[ A = \sec z - a_1 \sec(z - 1) - a_2 \sec^2(z - 1) - a_3 \sec^3(z - 1) \]  
\[ \text{dove } z = 1/\cos z \text{ e } z \text{ è la distanza zenitale, } a_1 = 0.0018167, \]

\[ a_2 = 0.002875, a_3 = 0.0008083. \]

10. Time synchronization

For a perfect timing of the observed phenomena, it is necessary to synchronize the clock in the PC with an atomic clock. For PC with internet connection it can be done with many software\(^2\). Who use Windows can simply set the corresponding clock option on the taskbar clock.

11. Guiding system

Defocusing the star on the imaging sensor will allow you to limit highly the noise from atmospheric scintillation. Of course every coin has two sides and you will have to select accurately your guiding. There are three main types of guiding systems largely used from amateurs:

1. self guiding system on the same sensor which lets in the same time both imaging and guiding
2. guiding sensor installed on the same focus plane of the main imaging sensor
3. detached guiding head with the sensor at the end of a refractor piggybacked on the main telescope with the imaging sensor

The first is not worth of further investigation here since it presents a few drawbacks which limit highly its use in the exoplanet imaging. In fact due to true nature of the interline device used to built the CCD in this kind of system, you must double the integration time given the same pixel intensity in the final image. In the second system the guiding sensor is situated on the same focal plane of the main imaging sensor very close to it. This system is very compact, light and the additional cost very low. Nevertheless defocusing the scope, the guide star will be defocused. Therefore the intensity of the guide star will decrease and you will risk to lose the star during the night because of the increasing airmass (if applicable), haze, passing clouds and so on. The first remedy to this is to set the binning to the highest allowed value. For example SBIG CCDs allow to set it to 3x3. Please note that the binning here is referred to the guiding system. The binning of the imaging sensor must be the lowest allowed that is 1x1.

Sometimes you can’t find a suitable guiding star (expecially if defocused) even turning around the CCD head. Many recent SBIG CCDs have a port which connect the main head to a remote guiding head which can be easily coupled with a refractor piggybacked on the main scope. This system is the most versatile but it is almost expensive considering the purchase of a separate CCD for the guiding, the little scope for the piggyback (generally a small refractor but a SCT can be suitable too) and the mounting rings. The final price can vary in the range from 500 USD up to 1500 USD. Another advantage of the separate scope for guiding is that the filter is set only in the imaging optical path and therefore the light falling on the guiding sensor is not reduced from it. This will let you to use a guide star fainter about 1-1.5 magnitude than in a dual sensor system. Again the coin has two sides and you have to consider that the piggyback scope has a lesser aperture than the main scope. So the guide star will have to be brighter than in a dual sensor system. Let see the photon balance in detail. If you use a 125mm SCT for guiding instead of the classical 80mm refractor, from the Pogson formula you can work out:

\[ \delta m = 2.5 \log \left( \frac{D_1}{D_2} \right)^2 \]  
\[ \text{That is, given the same integration time, the 125mm SCT will allow you to choose guide stars about 1 magnitude fainter than the 80mm refractor. By the way, the integration time highly depends on the mechanical quality of the mount. As a very first step in our analysis, the goodness of a mount is related to its periodic error. Of course other factors can affect a mount such as gear precision, gear shaft, etc. The periodic error in a typical mass market} \]
Table 5. Scintillation values in $10^{-3}$ units of relative flux ($dL/L$) for typical exposure time and some telescope aperture. Values for intermediate exposure times and aperture could be obtained by interpolation between adjacent values. Scintillation was calculated for an altitude of 300 m = 984.25 ft over the sea level. Lower altitudes provide greater values for scintillations, higher altitudes provide low scintillation values. Between 0 and 1000 m = 0 and 3281 ft, the scintillation change only of 0.1 mmag. Only over 2000 m = 6562 ft, the scintillation start to decrease significantly.

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fork mount can be as high as 30′′ peak-to-peak and depending on the image scale (i.e. arcsecond per pixel) the star could trail back and forth many pixels. In addition you have to consider the quantum efficiency (QE) of your guiding sensor. If the QE is higher than 20% compared to another sensor, using the Pogson formula seen above, you will work out a gain of 0.2 magnitudes given the same integration time. In the end it is worth of noting that the focal length of the guiding scope will have to match exactly the focal length of the main scope. In fact the littlest displacement of the guide star which the guiding sensor can detect, must be lesser than the displacement of the target star on the imaging sensor. For example, consider a guiding system made of a piggyback refractor 80mm f/6 and a guiding sensor pixel as large as 8x8 micron. If the main scope focal length is 2000mm, then you must verify the quantities:

$$\frac{2 \times 8 \times 206265}{80 \times 6} < \frac{9 \times 206265}{2000}$$

in this case 0.0033 < 0.0045 so the system is ok.
12. Time series photometry

Many software exist for doing photometry of time series of images. They are more or less efficient or adequate, but almost all produce results in magnitudes. For analyzing transit lightcurves it is necessary to build a reference star from sum of the fluxes of the bright stars surrounding the planet host star. Doing this with magnitudes add a little complication to the formulae, but also could be affected by rounding approximations in writing magnitudes. So it is more easy to work with flux (ADU counts), and to our knowledge there are only two software that provide results in fluxes: AIP $^4$ and IRIS $^5$. Of the two software only IRIS is freeware, and so we prefer to propose the use of this software.

12.1. Image reduction

Reduce images with dark frame, flat field, bias this step could be done with any reduction software.

12.2. File names

IRIS doesn’t work with sequential FITS files that in the name contains leading zeros. You need to remove them, the best way for doing it is using BulkFileRenamer (complex distortion). The recommended value is 1 for defocused images, 5 (complex distortion). The recommended value is 1 for defocused images. (The description of parameter M is taken from IRIS manual).

12.3. Set work path

Open IRIS, type CTRL+R, or alternatively goto File menu and open Settings.. Set the working path to the directory containing the images.

12.4. Convert images

Obtain image statistics, determine the maximum if it is lower than 32767 skip to Sec.12.5

If the maximum is greater than 32768 and bitpix=16 you need to convert the images. Note that this step is mandatory because IRIS cannot work with values from 0 to 65355, but only with images with counts between -32768 and +32768.

Click on the command line icon (the fourth from right), then type

\[ \text{convertsx3 imginp imgconv N} \]

where N is the total number of your images, you obtain N images named mgconv1.fit mgconv2.fit ...

12.5. Image alignment

12.5.1. Focused images

Perform the following procedure only if in your aligned images appear residual effects from field rotation. Load the image that will be used as reference, usually chose an image at the center of the sequence of planetary aligned images. From the menu Analysis chose Select Objects, and select some bright stars clicking on the center of the donut. From the command line type:

\[ \text{distor2 imgali imgalirot M N} \]

where imgali are the images aligned with planetary registration, N is the total number of your images, you obtain N images named imgalirot. M is the order of the quadratic equation used for fit the distortion. Range is between 1 (linear correction) and 5 (complex distortion). The recommended value is 1 for defocused images. (The description of parameter M is taken from IRIS manual).

12.5.2. Defocused images

Open the first image of your list. Use mouse cursor to select a rectangular region containing some bright stars. The region need to be large enough to contain at least two bright star, in order to provide a good reference region for the alignment algorithm.

Goto Processing menu, click on Planetary registration (1). In Input generic name write the first part of images to be aligned: imgconv Size of the sub-image, the standard value is 256, change it to 512, this permit a better results in case of image rotation. Output generic name, is the first part of the name of aligned images: imgali Number, is the number of images. Do not activate Spline.

Click OK, then you obtain your aligned images.

12.5.3. Image rotation

Perform the following procedure only if in your aligned images appear residual effects from field rotation. Load the image that will be used as reference, usually chose an image at the center of the sequence of planetary aligned images. From the menu Analysis chose Select Objects, and select some bright stars clicking on the center of the donut. From the command line type:

\[ \text{distor2 imgali imgalirot M N} \]

where imgali are the images aligned with planetary registration, N is the total number of your images, you obtain N images named imgalirot. M is the order of the quadratic equation used for fit the distortion. Range is between 1 (linear correction) and 5 (complex distortion). The recommended value is 1 for defocused images. (The description of parameter M is taken from IRIS manual).

12.5.4. Convert images

Obtain image statistics, determine the maximum if it is lower than 32767 skip to Sec.12.5

If the maximum is greater than 32768 and bitpix=16 you need to convert the images. Note that this step is mandatory because IRIS cannot work with values from 0 to 65355, but only with images with counts between -32768 and +32768.

Click on the command line icon (the fourth from right), then type

\[ \text{convertsx3 imginp imgconv N} \]

where N is the total number of your images, you obtain N images named mgconv1.fit mgconv2.fit ...

12.6. Verify the alignment

Goto View menu, and then Animate. Generic name, is the first part of aligned images imgali Number is the number of images. Delay, is the delay of visualization in milliseconds. Click on GO, and look at your sequence. If you see movement of the stars go back to Sec.12.5 and try to change the reference region or in the case of distortions change the reference stars. When you are satisfied with the alignment process press STOP.

A second procedure for the verification of the alignment is the blinking. From the command line type:

\[ \text{blink2 imgalirotB imgalirotC imgalirotE [Delay]} \]

Where B=1, C=N/2 is the number of the central image in your sequence, E=N is the number of the last image in the sequence. Type

\[ \text{blinkoff} \]

to stop the blinking procedure.

12.7. Create a sum image

Create a sum image for further reference. Goto Processing menu, and then Add a sequence. Input generic name, is the first part of aligned images imgali Number is the number of images. Click on Median and then OK, after some seconds you obtain the median image. Click on Save icon and insert the new file name (eg. sum.fit).

A second procedure for the verification of the alignment is the blinking. From the command line type:

\[ \text{blink2 imgalirotB imgalirotC imgalirotE [Delay]} \]

Where B=1, C=N/2 is the number of the central image in your sequence, E=N is the number of the last image in the sequence. Type

\[ \text{blinkoff} \]

to stop the blinking procedure.
12.8. PSF radius determination

Goto View menu, and select Slice. With your cursor draw a line over the brightest star in the field. The line need to be long enough to cover all the star and also a background region.

The Slice window will be opened automatically. Goto Options menu in this window, and click on Axis Setup. Accurately setup the Min and Max values for X axes and tick spacing, and click OK. Enlarge the Slice window dragging the bottom corner.

Obtain by eye a measure of the number of pixel from the center of the star to the surrounding background region. Annotate this value for the following photometric analysis, name this R1.

12.9. Aperture determination

Goto Analysis menu, click on Select objects. You need to work in a zoom x1, so if your are using a different zoom level, click the icon x1. With the cursor, click on the center of your brightest defocused star.

Return to Analysis menu, click on Select objects, this deactivate the section of object. If you are not satisfied with your center, first deactivate the selection tool, and reactivate it. This procedure eliminate the previous center list.

Goto to Analysis menu, click on Automatic Photometry. Input generic name, is the first part of aligned images imgali Number, is the total number of images. Output data file, is file that will contain the time series photometry, the file extension is fixed to lst. Uncheck Magnitude output. Pay attention it is the contrary of previous step. #1 to #5 contain the coordinates X,Y of your selected stars If not zero put VX and VY at 0. Activate No matching. Set Aperture photometry (this deactivate PSF photometry) Radius1 to the value obtained at the previous step, Radius2 to 1.15 times R1 and Radius3 to 1.42 times R1. Click OK and look at the Output window.

Now you have the results as fluxes in your output file. If you have more than 5 stars to photometer, repeat the procedure of this step until you reach the end of your list. Remember to change the output file name at each iteration.

12.12. Background determination

Per ottenerne le coordinate del punto su cui effettuare fotometria, basta avere la finestra File Image info aperta e cliccare al centro della zona che abbiamo individuato: nella finestra Image info appariranno le coordinate e y del punto. Andiamo adesso su Analysis Automatic photometry impostiamo normalmente la maschera come se stessimo per effettuare la fotometria di apertura di una stella, con un’unica importante differenza per: il secondo ed il terzo cerchio del sottoregime “Aperture photometry” vanno impostati a zero, mentre il primo cerchio deve essere delle stesse dimensioni della precedente fotometria sulle stelle.

13. Light curves analysis

Prima di tutto è necessario visualizzare le curve di luce delle singole stelle per stimare la loro qualità.

Per ottenere una curva di luce è sufficiente fare il grafico di JD contro ADU stella/(somma ADU ref) ed eventualmente riasfarlo (cioè ottenere la fase fotometrica dal JD), in definitiva le formule da utilizzare sono:

$$\phi = \text{modulo}\left(\frac{\text{HJD} - T_0}{P}\right)$$

HJD tempo dell’osservazione in HJD, $T_0$ tempo della centralità del transito in HJD, $P$ periodo orbitale in giorni.

Flusso = \( \frac{\text{ADU stella}}{\sum \text{ADU ref}} \)

Esempio di script per Gnuplot per produrre i grafici delle curve di luce

http://maeol.googlepages.com/grafici.plt

La creazione delle differenti combinazioni delle curve di luce si effettua con il programma lcurve-comb. Il programma crea tutte le combinazioni delle differenti curve di luce e determina quale sia la migliore combinazione che meglio approssima il transito teorico, che poi servirà per la successiva analisi.

La curva cosiottenuta potrebbe avere (quasi sicuramente) una pendenza che potrebbe essere originata o dalla massa d’aria o dal differente colore delle stelle utilizzate o dalla variabilità intrinseca di una delle stelle usate come riferimento. Usualmente

6 http://www.gnuplot.info
si corregge questo problema facendo un fit lineare dei punti fuori transito, e sottraendo il risultato di questo fit alla curva di luce. Questa correzione si effettua con il programma *lcure-detrend*.

...  

14. Fit dei parametri orbitali  
La determinazione dei parametri orbitali si effettua con il programma *lcure-analysis*. Il programma effettua un fit con una curva di luce trapezoidale e fornisce in output il momento della centralità del transito, la durata del transito e la profondità del transito.  
Una volta ottenuto questo fit si utilizza il programma *lcure-analysis-real* per ottenere il fit con una curva di luce dipendente dai parametri orbitali. Come valori di input vanno forniti gli output di *lcure-analysis*.

References  
Bessell, M. S. 1990, PASP, 102, 1181  
Table A.2. Periastron and apoastron for various orbital eccentricity calculated for semimajor axis $a = 1$ AU.

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Appendix A: Units

Appendix B: Links

Extrasolar Planets Encyclopedia di Jean Schneider: http://exoplanet.eu

I pianeti extrasolar in transito, raccolti e commentati da Frederic Pont: http://obswww.unige.ch/~pont/TRANSITS.htm

Il progetto Transitsearch.org di Gregory Laughlin: http://www.transitsearch.org

Il blog di Gregory Laughlin sui pianeti extrasolar: http://www.oklo.org

L’archivio delle curve di luce amatoriali dei transiti extrasolar di Bruce Gary: http://brucegary.net/AXA/x.htm


Conversione di coordinate: http://irsa.ipac.caltech.edu/cgi-bin/Lookup/wwlookup

Fasi lunari: http://stardate.org/nightsky/moon

Orari di sorgere e tramonto del Sole: http://stardate.org/nightsky/riseset

Conversione di JD in data standard e viceversa: http://aa.usno.navy.mil/data/docs/JulianDate.php

Appendix C: Air mass

Per ottenere la massa d’aria in funzione del tempo è necessario avere 3 numeri: la latitudine dell’osservatore ($lat$), la declinazione della stella ($DE$), l’angolo orario della stella ($HA$). La massa d’aria al momento $t$ (che equivale ad un certo angolo orario) è:

$$ y = 750 \times (\sin(lat) \sin(DE) + \cos(lat) \cos(DE) \cos(HA)) $$ (C.1)

$$ A = \sqrt{y^2 + 1499} - y $$ (C.2)

Infine per calcolare l’angolo orario in funzione del tempo espresso in JD è necessario conoscere: la longitudine dell’osservatore ($lon$), la latitudine dell’osservatore ($lat$), l’ascensione retta della stella ($RA$), la declinazione della stella ($DE$). Poi si utilizzano le seguenti formule, avendo l’accuratezza di esprimere le 4 coordinate in gradi (o radianti a preferenza):

$$ t = (\text{int}(JD) + 0.5 - 2451545)/36525 $$ (C.3)

$$ u = u_1 + u_2 \cdot (JD - 2451545) + u_3 \cdot t^2 - t^3 / u_4 $$ (C.4)

$$ ST = \text{modulo}(u, 360) $$ (C.5)

$$ LST = ST + LON $$ (C.6)

$$ HA = LST + RA $$ (C.7)

se HA>360 allora porre $HA = HA - 360$.

Appendix D: Filters transmission curves

Transmission curves for common filters.
Il tableau A.1 elenca i pianeti extrasolari noti per il loro transito. Dall’elenco sono esclusi i pianeti solo annunciati e non confermati per i quali non esiste una pubblicazione professionale di riferimento al momento attuale (novembre 2007).
Appendix E: Defocus radius

In this appendix we report the minimum defocus radius as a function of the apparent R magnitude of the stars and telescope diameter, calculated for fixed exposure times. For doing the calculation we assumed a telescope obstruction of 20%, a total optical transmission of 40%, a bandwidth of 130 nm, a CCD gain equal to 2.3, a pixel Full Well Capacity of 100000, and an air mass of 1.

The intersection between a magnitude line and a defocus curve for a fixed exposure time, provides a rough approximation for the R1 of the photometric aperture (see [12.3]).
defocus radii [px]

R mag = 20 cm

R mag = 25 cm
defocus radii [px]

R mag
d = 40 cm
30s, 60s, 90s, 120s, 150s, 180s

defocus radii [px]

R mag
d = 45 cm
30s, 60s, 90s, 120s, 150s, 180s
defocus radii [px]

R mag

d=50 cm

30s
60s
90s
120s
150s
180s
Appendix F: Scintillation

Scintillation noise for various telescope aperture and exposure times, expressed as relative flux (dL/L).
Appendix G: Transiting Planets Seasonal Visibility

Figure G.1. HD17156

Figure G.2. HD149026

Figure G.3. HD189733
Figure G.4. HD209458

Figure G.5. GJ436=TYC1984-2613

Figure G.6. Corot-exo-1=GSC04804-02268

Figure G.7. Corot-exo-2=GSC00465-01282

Figure G.8. Corot-exo-3=GSC00465-01645

Figure G.9. Corot-exo-4=GSC04800-02187
Figure G.10. HAT-P1=BD+37-4734s

Figure G.11. HAT-P2=TYC3065-1195

Figure G.12. HAT-P3=TYC3466-819

Figure G.13. HAT-P4=TYC2569-1599

Figure G.14. HAT-P5=TYC2634-1087

Figure G.15. HAT-P6=TYC3239-992
Figure G.16. HAT-P7 = TYC3547-1402

Figure G.17. HAT-P9 = TYC2463-281

Figure G.18. HAT-P10 = Wasp11 = TYC2340-1714

Figure G.19. Tres-1 = TYC2652-1324

Figure G.20. Tres-2 = GSC03549-02811

Figure G.21. Tres-3 = GSC03089-00929
Figure G.22. Tres-4 = TYC2620-648

Figure G.23. Wasp1 = TYC2265-107

Figure G.24. Wasp2 = GSC00522-01199

Figure G.25. Wasp3 = TYC2636-195

Figure G.26. Wasp10 = GSC02752-00114

Figure G.27. Wasp12 = TYC1891-1178
Appendix H: Observing report

This is an example of observing report.

- mag: V=11.25 R=10.80
- Ref1: GSC 3413:0210 B=12.30, R=11.10
- Ref2: GSC 3413:0011 V=11.15
- Ref3: GSC 3413:0187 V=12.06

Additional notes:
- we had tracking problems with the telescope pointing the field, in some images we had blurred stars
- Ref1: GSC 3413:0210 B=12.30, R=11.10
- Ref2: GSC 3413:0011 V=11.15
- Ref3: GSC 3413:0187 V=12.06

Notes on photometry:
- with Iris we used Ref1, Ref2 and Ref3 as ref stars
- used a large gap radius to avoid the close stars XO-2 and Ref1 could influence each other

Notes on weather conditions:
- h 18.30 DOME Temp 10.1 C; Humid 38%; CCD Temp -24.0 C
- h 1.00 DOME Temp 4.3 C; Humid 52%; CCD Temp -25.0 C
H.1. Template

=================================================================
REPORT ===
Object:
Date:
Site :
Coord:
Observers:
From:
To:
JD Time:
Sky:
Moon:
Filter:
Telescope diameter:
Focal length :
Focal ratio:
CCD:
FoV:
Scale:
Exposure:
Defocus :
Defocus size :
Acquisition software:
Data reduction software:
Calibration dark :
Calibration flat-field :
Photometry iris:
Information about object and ref stars (for photometry):
Obj1:
coord:
mag:
Ref1:
Ref2:
Chk1:
Additional notes:
Notes on photometry:
Notes on weather conditions:
=================================================================
END OF REPORT ===