Observing Guide to Transiting Extrasolar Planets

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Abstract

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1. 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 pratical 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 ($e > 0.8$).

$$D = \frac{2(R_s + R_p)r_t}{\sqrt{G(M_s + M_p)a(1 - e^2)}} \sqrt{1 - \frac{r_t^2 \cos^2 i}{(R_s + R_p)^2}} \tag{1}$$

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 is the planetary orbital semimajor axis, e is the planetary orbital eccentricity, i is the planet inclination, and

$$r_t = \frac{a(1 - e^2)}{1 + e\cos(\pi/2 - \omega)} \tag{2}$$

ω is argument of periastron of the planet.

Depth of transit in flux units

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

Depth of transit in magnitudes

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

2. Synchronizing time

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, e.g.: Time Memo, Atomic Clock Sync The available programs are many, and you can found a list in this web page: `http://www.oink.com/misc/timesync.html`. Who use Windows XP can simply set the corresponding clock option on the Windows clock. An interesting freeware program from G.Benintende, which you can download at `http://www.astrogb.com/astroalarm.htm`. If you have not set Automatic fix, do it manually before the start of each observing session.

3. CCD

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 to not fall below 60%. During observation the autoguide and cooling must always turned on. General rules for the observations:

- 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
- work only in the regime of linear response of the camera
- do not to use binning, use only binning 1×1

The frequent question is why not use a 2×2 binning or greater. The advantages to use this type of binning compared to 1×1 binning are:

1. decrease the time reading (is already low)
2. decrease the RON (is already low because we are working at high count level)

on the other side we have disadvantages:

1. 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)
2. short exposure times, increasing the scintillation
3. major sensibility to hot/dead/cosmic pixel, if one pixel is hot/dead/cosmic, all the binned pixel suffer from this one
4. with the same defocus the number of pixel decrease, as a consequence the photometric precision is lower and the Signal to Noise Ratio (SNR) decrease

write more about cooling!!!

4. Calibration images

Fo the calibration images:

- the dark must have the exposure same time of the photometric images
- the flat field should be obtained at the beginning or at the end of the observing session
- must be obtained also the bias 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 transits.

add the Papini technique about dark frames

5. 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 to have a photometric (Johnson or Cousin) filter, but it is necessary that the filter cuts the blue wavelengths that are those largely concerned by the scintillation. In the absence of a R filter it is possible to use V filter.

If you have photographic filter an approximate R filter can be normally obtained combining OG570 + KG3 Schott filters, or any another combination of OG and KG filters. Another possiblity is the use of Wratten filters, that are selled by many manufactures. For red you can use filters number 24, 25, 26, 29 and 92.

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.

6. Telescope requirements

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.

7. 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):

$$\sigma_{scint} = \frac{0.09 d^{-2/3} A^{1.75} \mathrm{e}^{-h/8000}}{\sqrt{2 t_{exp}}} \quad (5)$$

where d is the telescope diameter in centimeters, A is the airmass, h is the height over sea level in meters, t_{exp} is the esposure time in seconds.

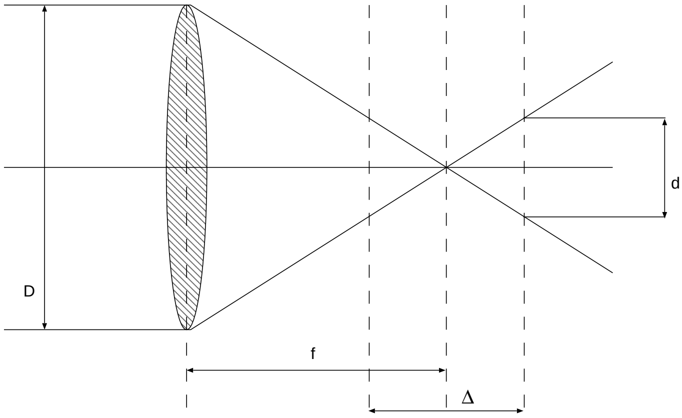


Figure 1. caption

In Tab. 1 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.

8. How to photometer bright stars: defocus technique

need 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

By geometry (Fig.1) we have:

$$\frac{D}{f} = \frac{d}{\Delta/2} \quad (6)$$

$$\Delta = \frac{2 d f}{D} \quad (7)$$

For a given blur circle diameter (as specified in a design, for example), the depth of focus is proportional to f/D

...

9. 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

z	air mass	30 s	60 s	90 s	120 s	150 s	180 s
Diameter 10 cm = 3.94 in							
90	1.00	2.4	1.7	1.4	1.2	1.1	1.0
75	1.04	2.6	1.8	1.5	1.3	1.1	1.0
60	1.15	3.1	2.2	1.8	1.5	1.4	1.3
45	1.41	4.4	3.1	2.5	2.2	2.0	1.8
30	2.00	8.1	5.7	4.7	4.0	3.6	3.3
15	3.82	25.1	17.8	14.5	12.6	11.2	10.3
Diameter 20 cm = 7.87 in							
z	air mass	30 s	60 s	90 s	120 s	150 s	180 s
90	1.00	1.5	1.1	0.9	0.8	0.7	0.6
75	1.04	1.6	1.1	0.9	0.8	0.7	0.7
60	1.15	2.0	1.4	1.1	1.0	0.9	0.8
45	1.41	2.8	2.0	1.6	1.4	1.2	1.1
30	2.00	5.1	3.6	2.9	2.5	2.3	2.1
15	3.82	15.8	11.2	9.1	7.9	7.1	6.5
Diameter 30 cm = 11.81 in							
z	air mass	30 s	60 s	90 s	120 s	150 s	180 s
90	1.00	1.2	0.8	0.7	0.6	0.5	0.5
75	1.04	1.2	0.9	0.7	0.6	0.6	0.5
60	1.15	1.5	1.1	0.9	0.7	0.7	0.6
45	1.41	2.1	1.5	1.2	1.1	0.9	0.9
30	2.00	3.9	2.7	2.2	1.9	1.7	1.6
15	3.82	12.1	8.5	7.0	6.0	5.4	4.9
Diameter 40 cm = 15.75 in							
z	air mass	30 s	60 s	90 s	120 s	150 s	180 s
90	1.00	1.0	0.7	0.6	0.5	0.4	0.4
75	1.04	1.0	0.7	0.6	0.5	0.5	0.4
60	1.15	1.2	0.9	0.7	0.6	0.6	0.5
45	1.41	1.8	1.2	1.0	0.9	0.8	0.7
30	2.00	3.2	2.3	1.8	1.6	1.4	1.3
15	3.82	10.0	7.0	5.8	5.0	4.5	4.1
Diameter 50 cm = 19.69 in							
z	air mass	30 s	60 s	90 s	120 s	150 s	180 s
90	1.00	0.8	0.6	0.5	0.4	0.4	0.3
75	1.04	0.9	0.6	0.5	0.4	0.4	0.4
60	1.15	1.1	0.7	0.6	0.5	0.5	0.4
45	1.41	1.5	1.1	0.9	0.8	0.7	0.6
30	2.00	2.8	2.0	1.6	1.4	1.2	1.1
15	3.82	8.6	6.1	5.0	4.3	3.8	3.5
Diameter 60 cm = 23.90 in							
z	air mass	30 s	60 s	90 s	120 s	150 s	180 s
90	1.00	0.7	0.5	0.4	0.4	0.3	0.3
75	1.04	0.8	0.5	0.4	0.4	0.3	0.3
60	1.15	0.9	0.7	0.5	0.5	0.4	0.4
45	1.41	1.3	0.9	0.8	0.7	0.6	0.5
30	2.00	2.4	1.7	1.4	1.2	1.1	1.0
15	3.82	7.6	5.4	4.4	3.8	3.4	3.1

Table 1. 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 scintilliation change only of 0.1 mmag. Only over 2000 m = 6562 ft, the scintilliation start to decrease significantly.

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.

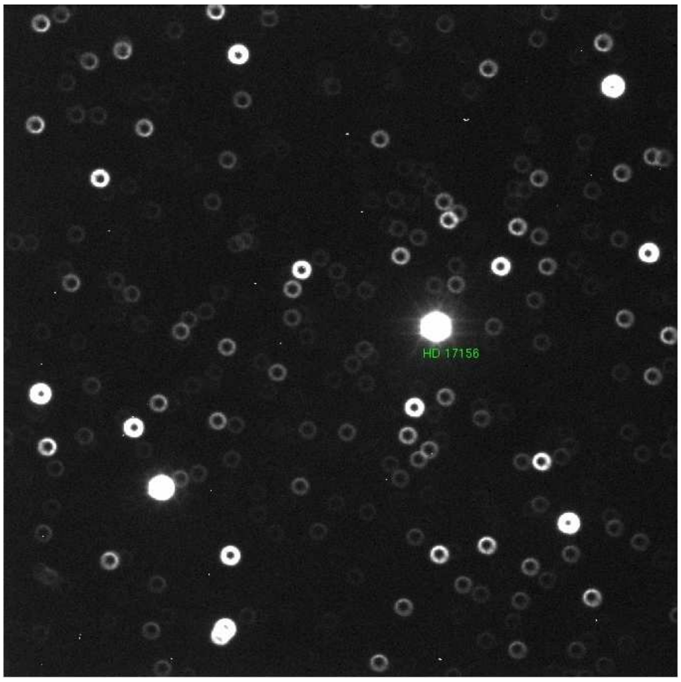


Figure 2. Example of a type defocused image of HD 17156. The image was obtained at the 1.2m at Observatoire d'Haute Provence the 2007/12/3. Exposure time was 25 s with R filter.

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.

Sometime 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:

$$\delta m = 2.5 \log \left(\frac{D1}{D2} \right)^2 \tag{8}$$

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 depnds 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 curse other factors can affect a mount such as gear precision, gear shaft, etc.

The periodic error in a typical mass market 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:

$$\frac{2 \times 8 \times 206265}{80 \times 6} \frac{1}{10} < \frac{9 \times 206265}{2000}$$

in this case $0.0033 < 0.0045$ so the system is ok.

10. Focused and Defocus 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 complications 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[1] and IRIS[2]. Of the two software only IRIS is freeware, and so we prefer to propose the use of this software.

10.1. Image reduction

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

10.2. 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[3] Oherwise you can convert with a simple bash script (you need to install Cygwin), as show in the following example.

```
ls *fit | while read f
do
   let i=i+1
   cp $f img_inp$i.fit
done
```

[1] http://www.wvi.com/~rberry/imageprocessing/aip4win/aip4win

[2] http://www.astrosurf.com/buil/us/iris/iris.htm

[3] http://www.bexonsoft.com/BulkFileRenamer/index.htm

10.3. Set work path

Open IRIS, type CTRL+R. Set the working path to the directory containing the images.

10.4. Convert images

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

```
convertsx imginp imgconv N
```

where N is the total number of your images, you obtain N images named `mgconv1.fit imgconv2.fit ...` with pixel values ranging from 0 to 32768 (15 bit). Note that this step is mandatory because IRIS cannot work with values from 0 to 65355 (the normal 16 bit range)

10.5. Image alignment

10.5.1. Focused images

TBW

10.5.2. 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 aligment 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.

10.6. 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 ms. Click on GO, and look at your sequence. If you see movement of the stars go back to point **??**) and try to change the reference region. When you are satisfied with the alignment process press STOP.

10.7. Create a sum image

Create a sum image for further reference. Goto Processing menu, and then Add a sequence. Input eneric 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). Repeate the operation and save the file as FITS and JPG. This file could be edited with image manipulation software for annotating the stars selected for the photometry and their names.

10.8. 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.

10.9. 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 objects. 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. Check Magnitude output, set Magnitude constant to 0. `#1` contain the coordinates X,Y of your star, put VX and VY at 0. If active `#2` to `#5` deactivate them. Activate No matching. Set Aperture photometry (this deactivate PSF phtometry) Radius1 to the value of R1, Radius2 to 1.5 times R1 and Radius3 to 2 times R1. Click OK and look at the Output window. Last line report the error on the time series in magnitudes, named as Deviation. Return to Automatic photometry and increase (or decrease) the value of Radius1 by one pixel and click OK. Look at the results in Output window. Do this procedure iteratively until you obtain the small possible Deviation value and annotate the corresponding value of Radius1.

10.10. Make stars list for photometry

Goto Analysis menu, click on Aperture photometry. Set Circle number to 3, check Median background, and Magnitude constant to 25. Set Radius1 to the value obtained at the previous step, Radius2 to 3 times R1 and Radius3 to 4 times R1. Click OK and click on the image near the center of the brigthest stars. The results of aperture photometry are in the Output window. Annotate the coordinates of the stars that are within 3 magnitudes from the star under study. At the end deactivate the Aperture photometry tool going to Analysis menu, click on Aperture phtotometry, and click on Cancel.

10.11. Time serie photometry

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 defocused stars. Start from the star under study and click on the other in order of descending magnitudes. You can select a maximum of 5 stars. Return to Analysis menu, click on Select objects, this deactivate the section of objects. If you are not satisfied with your center, first deactivate the selection tool, and reactivate it. This procedure eliminate the previous centers 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 phtometry) Radius1 to the value obtained at the previous step, Radius2 to 3 times R1 and Radius3 to 4 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, repeate the procedure of this step until you reach the end of your list. Remember to change the output file name at each iteration.

11. Observing report

11.1. Example of observing report

- Object: XO-2
- Date: 2008 01 24
- Site : Astronomical Observatory - University of Siena - Italy
- Coord: Lat +43 18 45 N - Long 11 20 12 E
- Observers: A.Borsi, M.Conti, A.Marchini, F.Marchini
- From: 2008.01.24 h 18.30 UT
- To: 2008.01.25 h 01.15 UT
- JD Time: UT GEOCENTRIC (with NO heliocentric correction)
- Sky: clear, seeing 3-4/5
- Moon: 2 days after full moon (16.4 days old), 93% illuminated, rises h 18.34, more than 50 degrees from field
- Filter: V Johnson-Cousins (Schuler)
- Telescope diameter: 25 cm
- Focal length : 1600 mm
- Focal ratio: 6.3
- CCD: Starlight Xpress SX-L8
- FoV: 16.5x16.5 arcmin
- Scale: 1.93 arcsec/px
- Exposure: 90 s
- Defocus : Yes (Y = defocus, N = no defocus)
- Defocus size : 10 px (width of the FWHM)
- Acquisition software: Astroart
- Data reduction software: Iris
- Calibration dark : Yes (Yes/No)
- Calibration flat-field : Yes (Yes/No)
- Photometry iris: R1=5 px ; R2=26 px ; R3=7 px
- Information about object and ref stars (for photometry):
- Obj1: XO-2 = TYC/GSC 3413:0005
- coord: RA 07 48 06.468 DE +50 13 32.96
- 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
- - the sky background was noisy due to the presence of the moon
- - we used 90 s. of exp.time; for the problems mentioned above we had a low Signal to Noise Ratio in many images
- - flat-field frames (dome flats) and the relative dark-frames taken at the end of the session
- 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

12. 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 ===
```

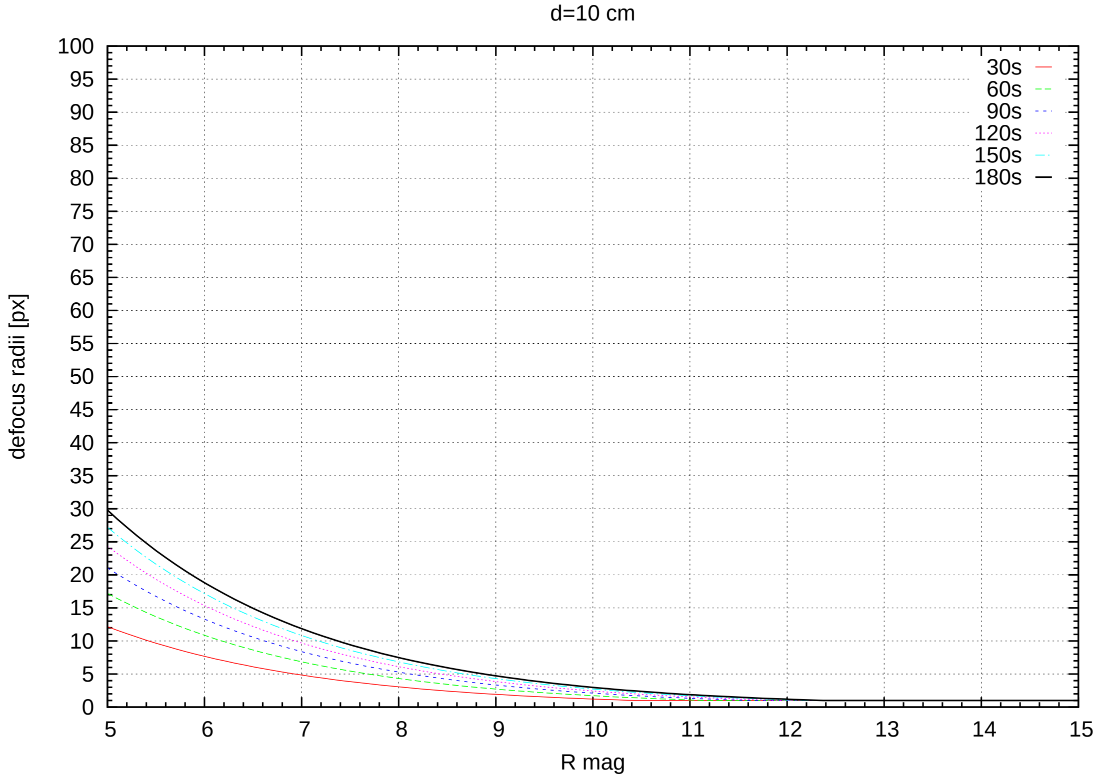
References

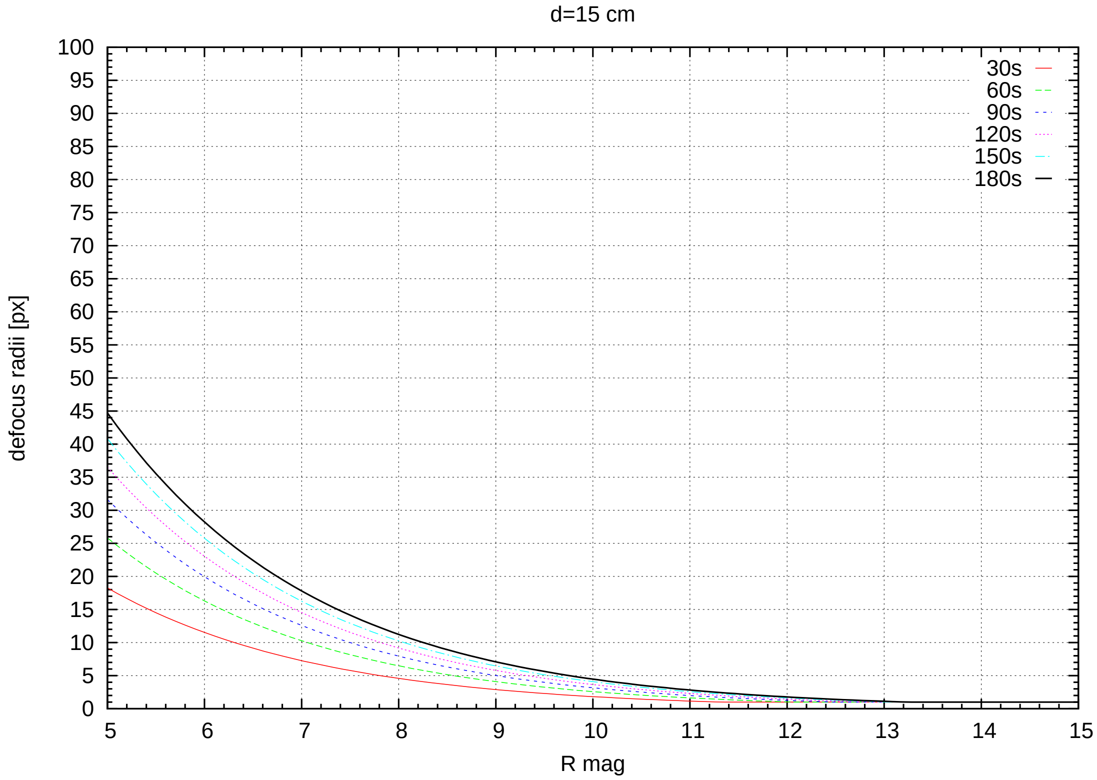
Dravins, D., Lindegren, L., Mezey, E., & Young, A. T. 1998, PASP, 110, 610
Tingley, B., & Sackett, P. D. 2005, ApJ, 627, 1011

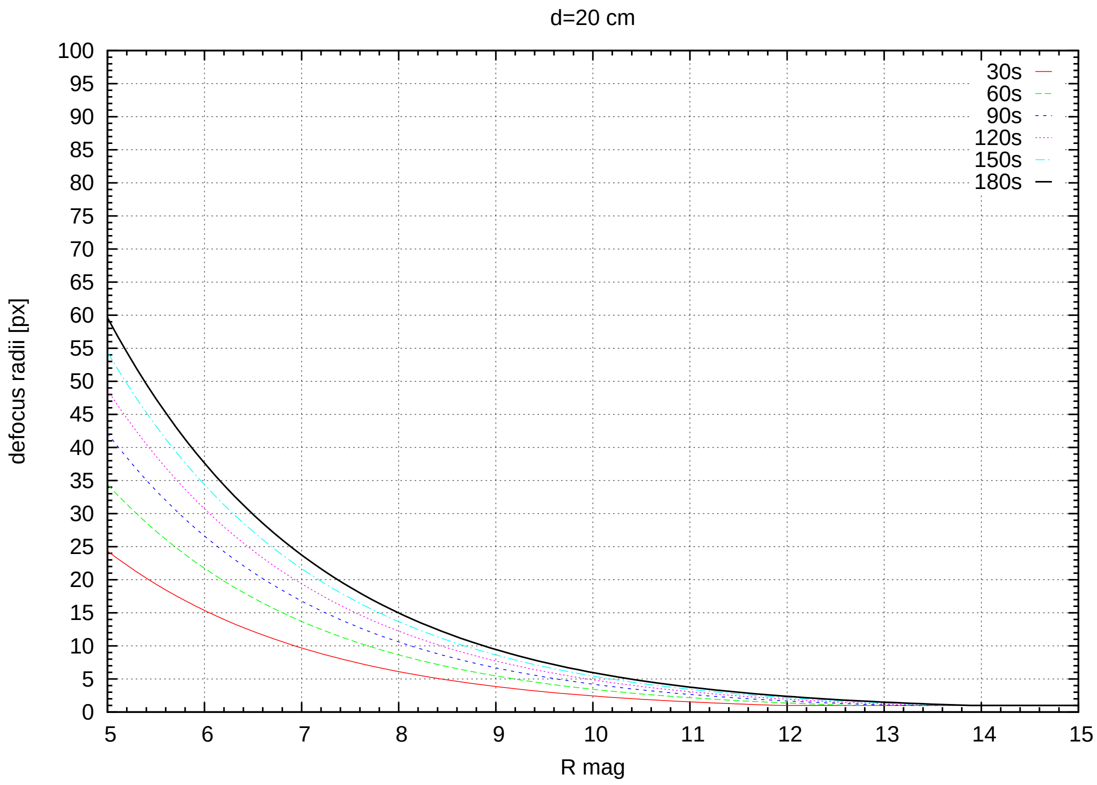
Appendix A: Defocus radius

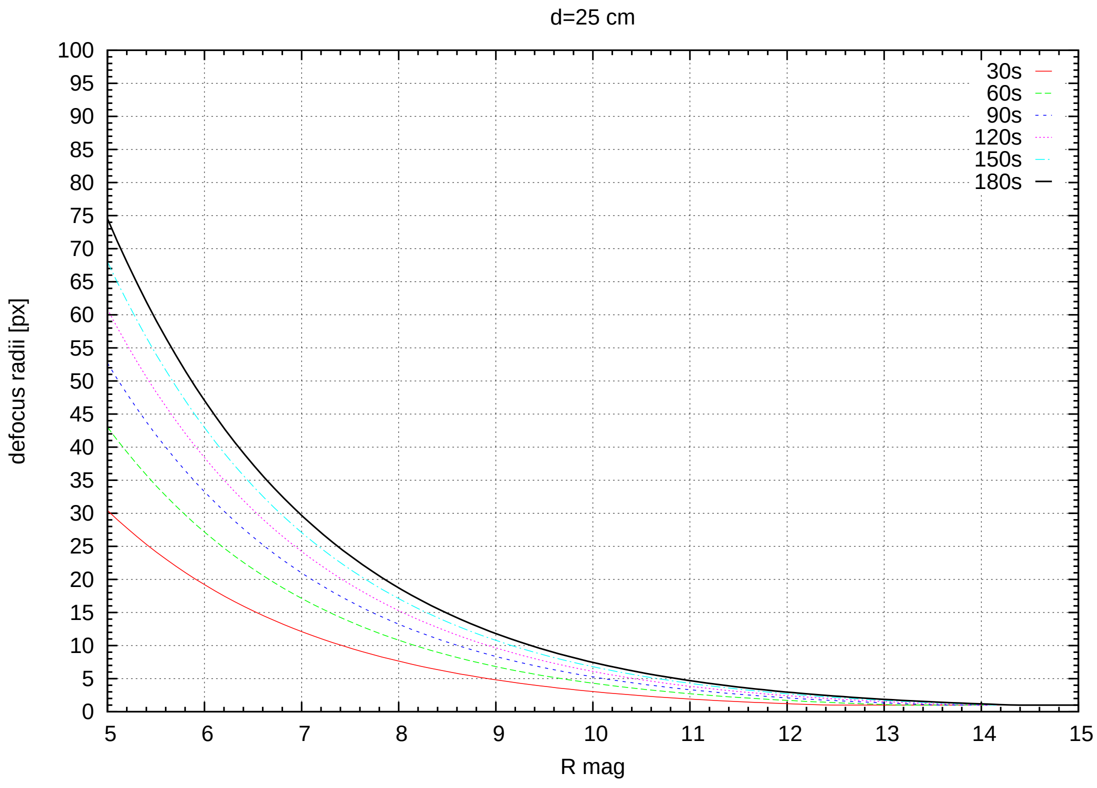
In this appendix we report the minimum defocus radius as a function of the apparent R magnitude of the stars and telescope diameter, calculated for fixed exposure times. For doing the calculation we assumed a telescope obstruction of 20%, a total optical transmission of 40%, a bandwith of 130 nm, a CCD gain equal to 2.3, a pixel Full Well Capacity of 100 000, and an airmass of 1.

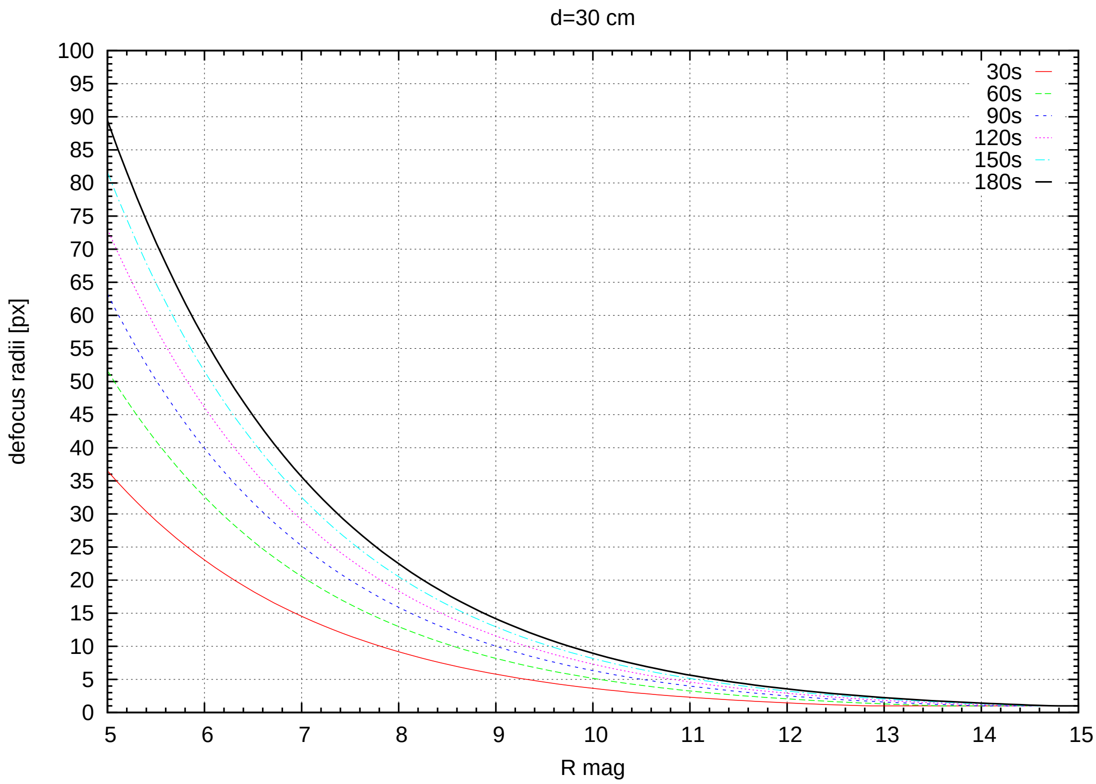
The intersection between a magnitude line and a defocus curve for a fixed exposure time, provide a rough approximation for the R1 of the photometric aperture (see 10.9).

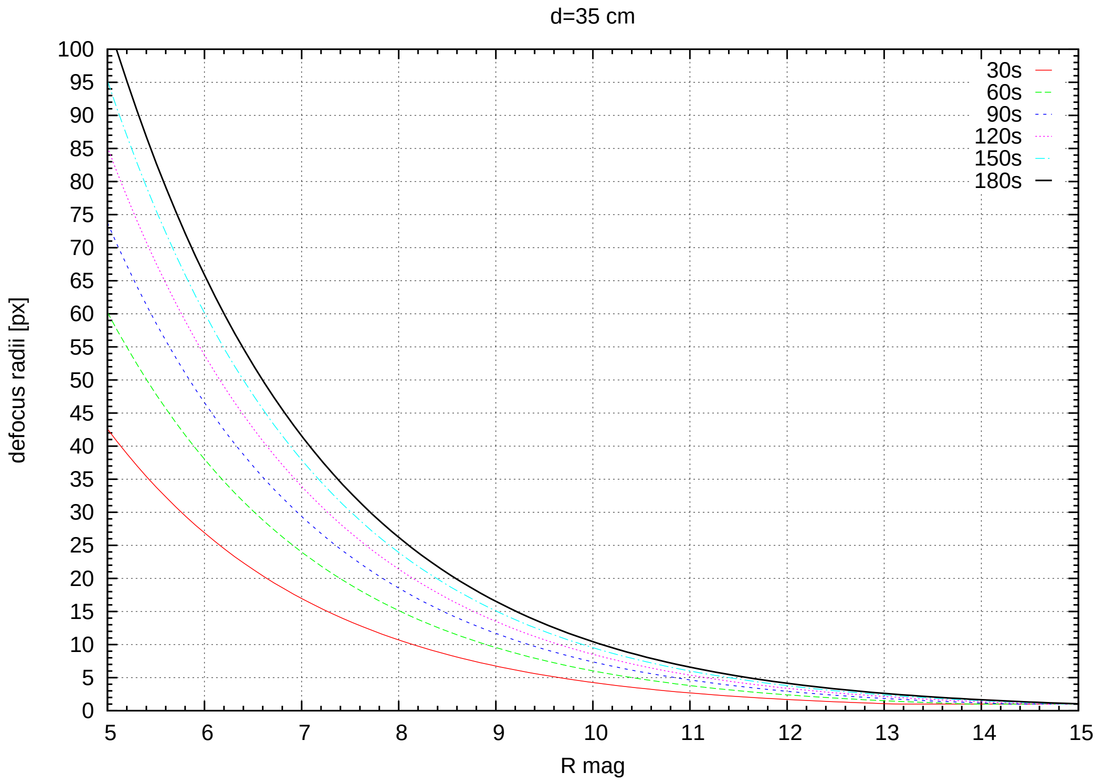

d=10 cm
defocus radii [px]
R mag
30s
60s
90s
120s
150s
180s
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
5
6
7
8
9
10
11
12
13
14
15

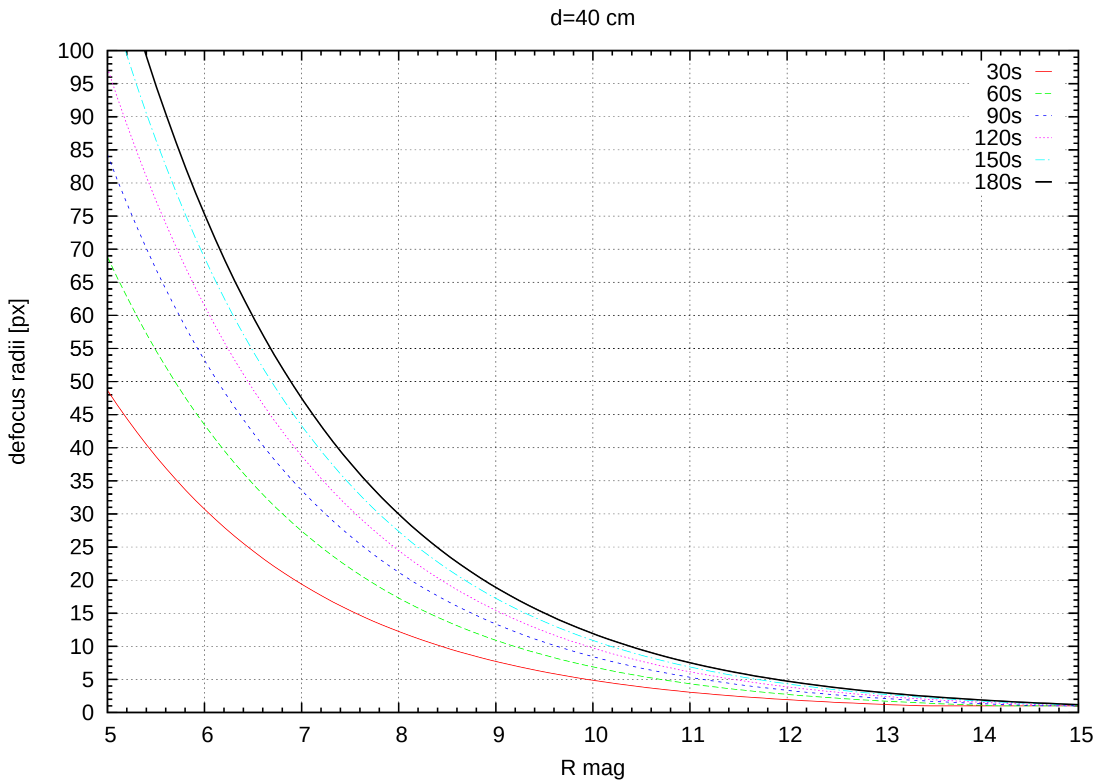

d=15 cm
defocus radii [px]
R mag
30s
60s
90s
120s
150s
180s
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
5
6
7
8
9
10
11
12
13
14
15

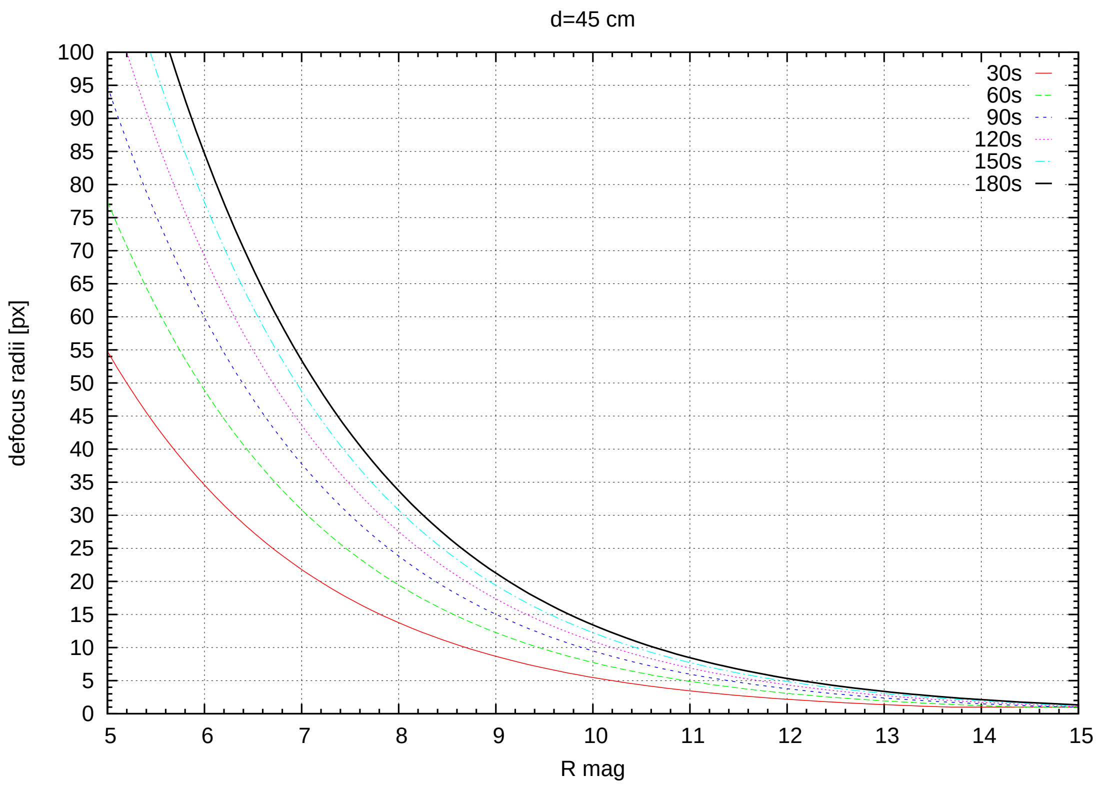

d=20 cm
defocus radii [px]
R mag
30s
60s
90s
120s
150s
180s

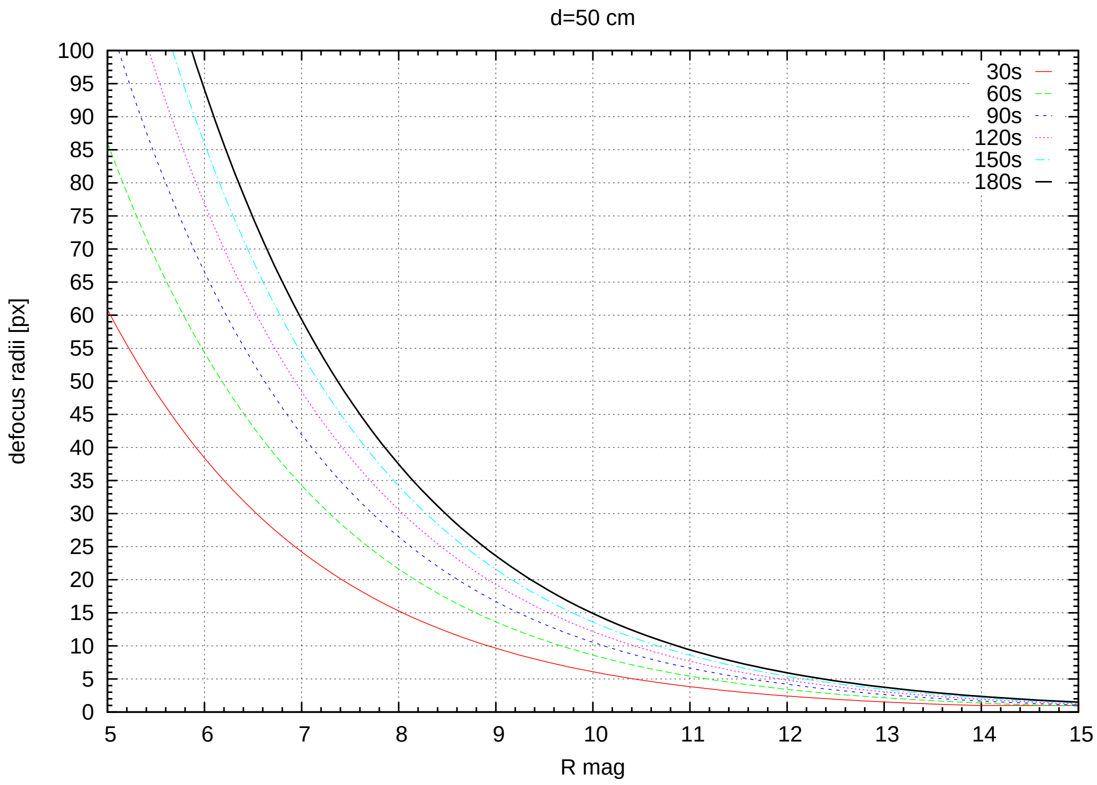

d=25 cm
defocus radii [px]
R mag
30s
60s
90s
120s
150s
180s


d=30 cm
defocus radii [px]
R mag
30s
60s
90s
120s
150s
180s
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
5
6
7
8
9
10
11
12
13
14
15


d=35 cm
defocus radii [px]
R mag
30s
60s
90s
120s
150s
180s
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
5
6
7
8
9
10
11
12
13
14
15

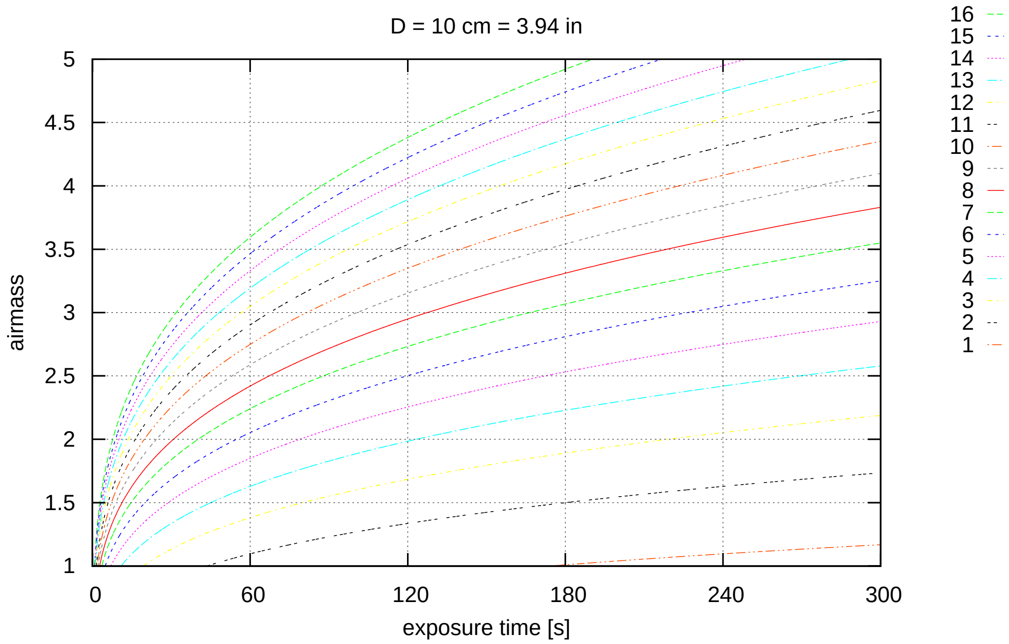

d=40 cm
defocus radii [px]
R mag
30s
60s
90s
120s
150s
180s
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
5
6
7
8
9
10
11
12
13
14
15

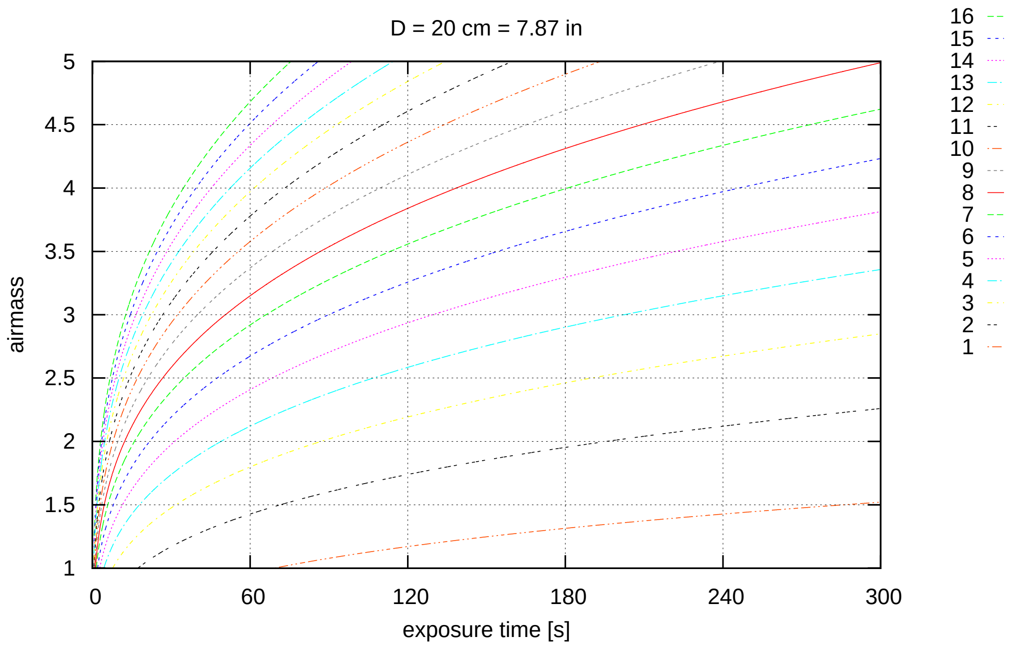

d=45 cm
defocus radii [px]
R mag
30s
60s
90s
120s
150s
180s
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
5
6
7
8
9
10
11
12
13
14
15

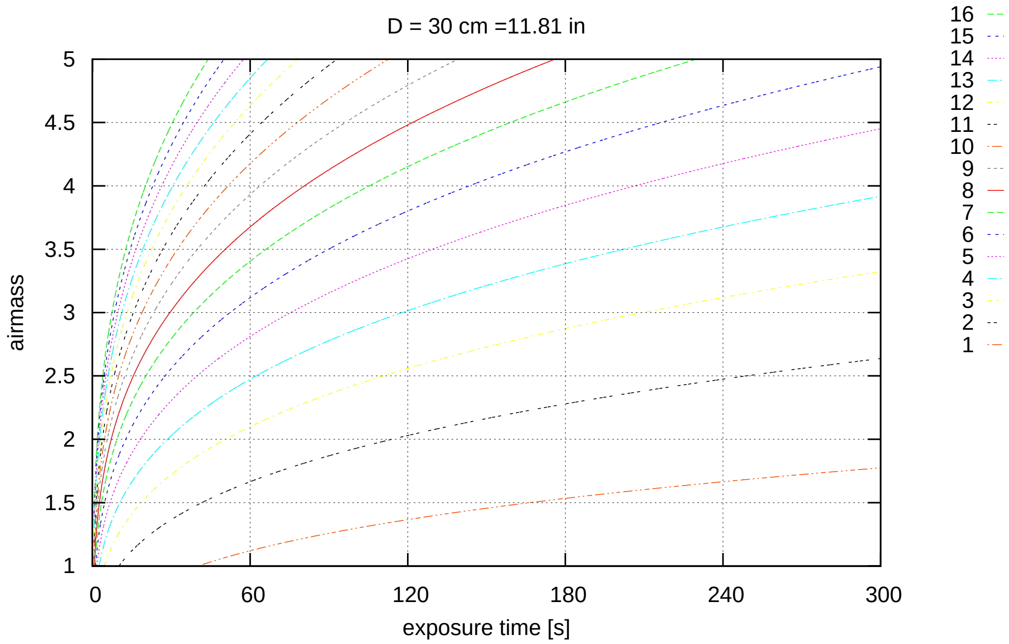

d=50 cm
defocus radii [px]
R mag
30s
60s
90s
120s
150s
180s
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
5
6
7
8
9
10
11
12
13
14
15

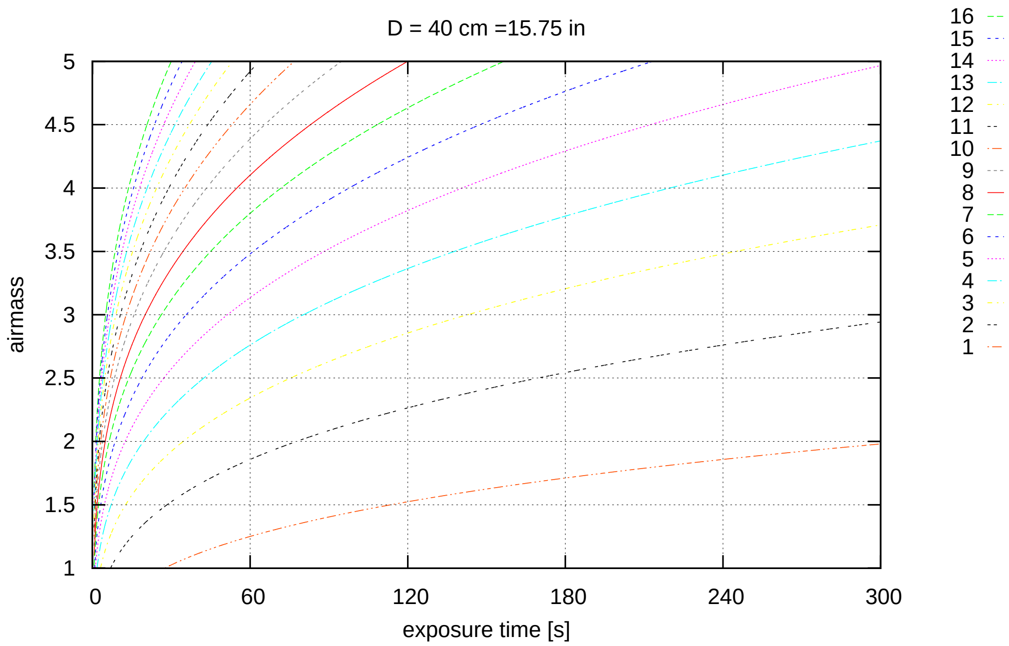
Appendix B: Scintillation

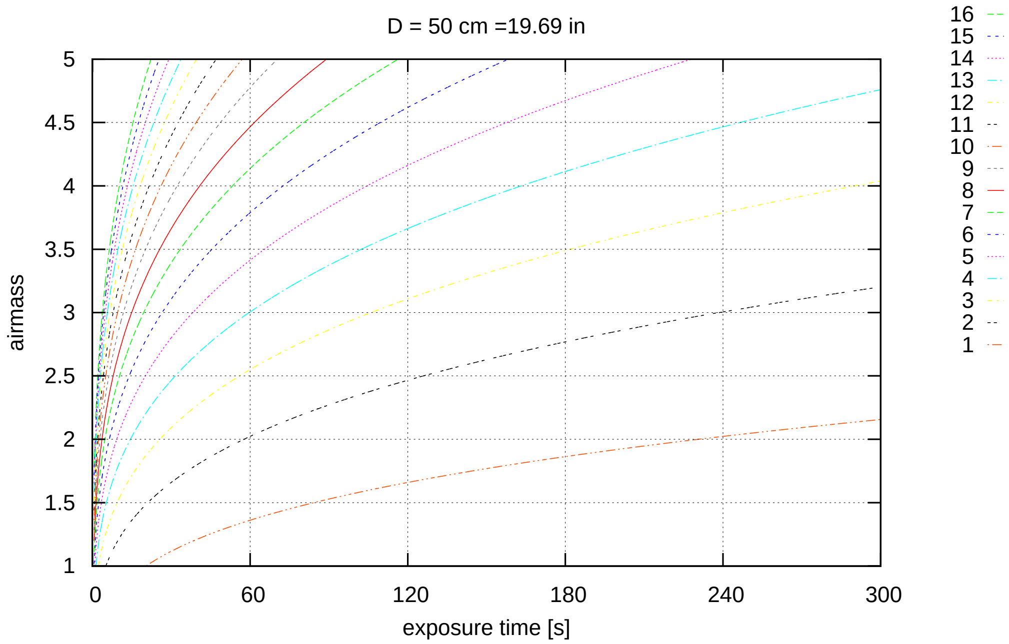
Scintillation noise for various telescope aperture and exposure times, expressed as relative flux (dL/L).

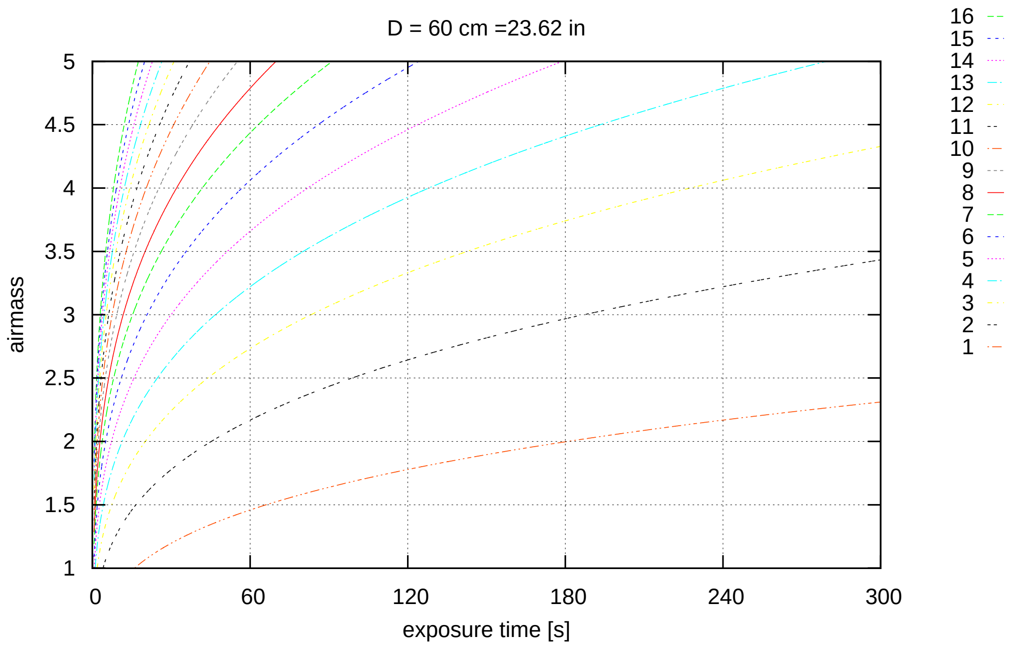

D = 10 cm = 3.94 in
airmass
exposure time [s]
0
60
120
180
240
300
1
1.5
2
2.5
3
3.5
4
4.5
5
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1

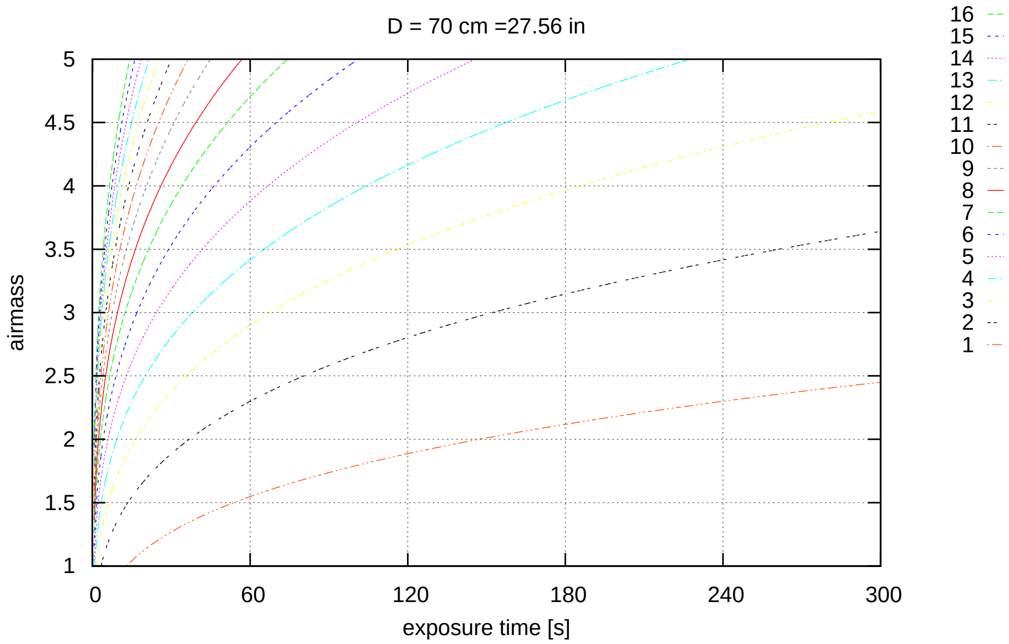

D = 20 cm = 7.87 in
airmass
exposure time [s]
0
60
120
180
240
300
1
1.5
2
2.5
3
3.5
4
4.5
5
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1

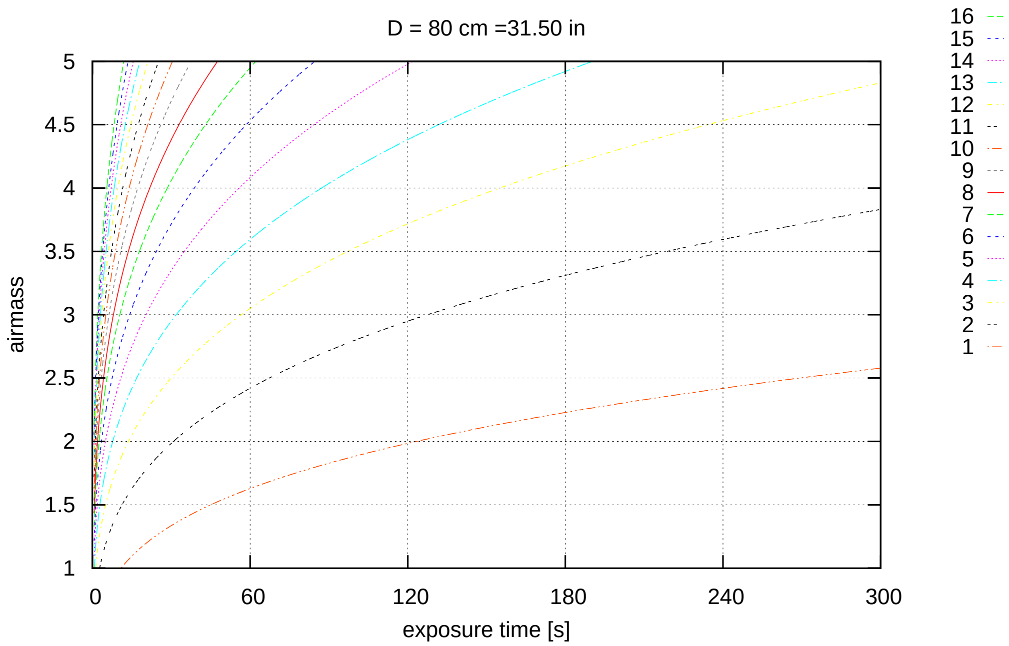

D = 30 cm =11.81 in
airmass
exposure time [s]
0
60
120
180
240
300
1
1.5
2
2.5
3
3.5
4
4.5
5
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1


D = 40 cm =15.75 in
airmass
exposure time [s]
0
60
120
180
240
300
1
1.5
2
2.5
3
3.5
4
4.5
5
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1


D = 50 cm =19.69 in
airmass
5
4.5
4
3.5
3
2.5
2
1.5
1
0
60
120
180
240
300
exposure time [s]
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1


D = 60 cm =23.62 in
airmass
5
4.5
4
3.5
3
2.5
2
1.5
1
0
60
120
180
240
300
exposure time [s]
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1


D = 70 cm =27.56 in
airmass
5
4.5
4
3.5
3
2.5
2
1.5
1
0
60
120
180
240
300
exposure time [s]
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1


D = 80 cm =31.50 in
airmass
5
4.5
4
3.5
3
2.5
2
1.5
1
0
60
120
180
240
300
exposure time [s]
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1