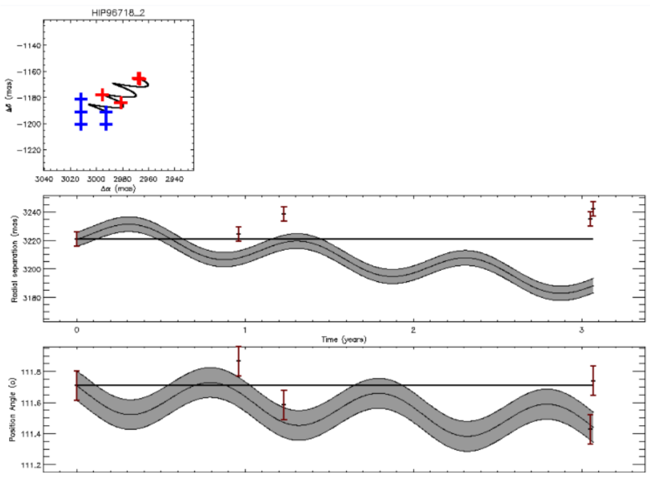
Instructions for CPM photometry

1. Ensure you have both the script: cpm_photometry.py (can be found on github or under DangerZone/astrometry in analysis) and your image in the same directory. The script can only process one image at a time so ensure the images of the star/candidate for the different epochs are separate.
2. Open a ds9 window and note the maximum and minimum x and y values of a box surrounding the candidate. For example, if the candidate's position is approximately (821,611), you could try defining x limits of 800 and 840, and y limits of 600 640.
3. Run the python script using **python cpm_photometry.py** in Ubuntu or **run cpm_photometry.py** in Jupyter notebook.
4. Input the name of the image you wish to analyse.
5. Enter the x and y bounds as requested by the script.
6. The script will output "Position is…" and then the candidate position in ds9 coordinates (lowest left-hand pixel is (1,1)). It will also output an image with the position of the candidate marked.
7. You will then be asked if you wish to do photometry on this source too, press 1 for yes, any other number for no. **Photometry is an extra feature and is not required if you just want to do CPM**.
8. Pressing any other number will end the program.
9. Repeat this process for the star if the image is not centred.
10. Find the difference between the candidate and stellar coordinates and ensure the+- signs are correct (the top left of the image is ++).
11. **For all images:** convert these coordinates into polar coordinates to rotate the image by angle β. This is 0.252° for data before 2015apr13, 0.262° after 2015apr13.
12. If you are working with raw data, you will have to rotate the image so north is upwards. The coordinates will generally be rotated by PARANG degrees **anticlockwise** (look in image header) (if PARANG is positive, rotate anticlockwise, if it is negative, rotate clockwise). If (look in header again) ROTPOSN-INSTANGL≠0, further rotation corrections are required. Refer to:
    https://github.com/jluastro/nirc2_distortion/wiki?fbclid=IwAR0u1ypp7HzGZqmAQ1fUL_vZMeaOe7WI0ErANCyiyktV_7IlZ0tYIYT5T_c#dist_post2015
    for more information about rotation corrections, distortion corrections, values of β and plate scales.
13. Convert this new position back into Cartesian coordinates centred on the star (check again +- signs are correct) and multiply the pixel values by the plate scale to retrieve the candidate position in mas. This scale is 9.952mas/pix for data before 2015apr13, 9.971mas/pix for after 2015apr13.
14. Connect to analysis and open an X server, I used mobaXterm but any that has a terminal and can plot data will do.
15. Login to your personal section of the VPN using: 'ssh -XY abc123@analysis.astro.ex.ac.uk', where abc123 is replaced with your username. **Don't forget the '-XY' or you will be unable to plot anything.**
16. Enter 'cd..' twice, then navigate to the files needed using: 'cd data/shinkley/Keck_Data/completed_stars/DangerZone/astrometry/Jake/HIP96718.
    n.b the capitals are correct.
17. Make sure the file contains the following documents: filestar_HIP96718_hannah_2.txt, journal_hip89925.idl and movement_v3_hip16095.pro.

18. Access the filestar file using nano by: ‘nano filestar_HIP96718_hannah_2.txt’, any text editor will do but nano seems to be the fastest to load.

```
HIP96718_2
03 27 18.6760                                                                          ;RA  (2000)
12 44 7.0275                                                                           ;DEC (2000)
9.534                                                                                  ;PPM_RA (mas/yr)
0.249                                                                                  ;ERREUR PPM_RA (mas/yr)
-7.967                                                                                 ;PPM_DEC (mas/yr)
0.200                                                                                  ;ERREUR PPM_DEC (mas/yr)
87.64                                                                                  ;DISTANCE (pc)
7.68                                                                                   ;ERREUR DISTANCE (pc)
0.000
0.000
5                                                                                      ;NBRE D'EPOQUE(S)
2013 10 17          2014 10 03          2015 01 10          2016 11 05          2016 11 11
2992.42             2992.42             3011.48             3011.48             3011.48
4.976               4.976               4.976               4.976               4.976
-1191.25            -1200.78            -1191.25            -1181.72            -1200.78
4.976               4.976               4.976               4.976               4.976
```

19. You should obtain above. Keep the name of the star at the top the same if you wish to avoid changing large amounts of the other two documents. The first two number rows are RA (in units of time) and dec for the star, input the values for your star which can be found on SIMBAD online. The next four rows are proper motion (PPM) in the RA direction, uncertainty for that PPM, PPM in the dec direction and uncertainty for that PPM. Again, use SIMBAD for these values. The next two rows are distance (PC) and uncertainty. Leave the two rows of 0 as 0 (this is parallax, but the script is set to read distance only, so leave at 0) and change the 5 to the number of epochs you analysed.
20. Record the separation for each epoch in filestar, each epoch is listed as; date, x difference (mas), x uncertainty, y difference (mas) and y uncertainty. The uncertainty is assumed to always be 4.976mas for both axes.
21. Save and close this file using: ‘{control} o, {enter}, {control} x’. Open the movement file using: ‘nano movement_v3_hip16095.pro’.
22. Save and exit this file and open the journal document using: ‘nano journal_hip89925.idl’.
23. Ensure that the references to the other documents are the correct names, save and close.
24. Type ‘bash’ then ‘idl’, wait for the idl screen to appear before typing: ‘@journal_hip89925.idl’
25. Close the window that appears and reopen by typing ‘@journal_hip89925.idl’, this ensures any previous work has been overwritten.
26. You should see three plots;



27. The top is the RA and dec positions of the candidate relative to the star for each epoch corresponding to the blue points. The wave is the path a background star with similar PPM to the host star would trace due to parallax and its PPM. As the candidate is approximately static in these frames, it is very likely to be gravitationally bound to the star, making it an exoplanet. The other two graphs are radial distance from the host star

vs time and angular position of the exoplanet vs time (note 0° is located at 12 O clock and the angles increase anticlockwise).

28. Exit idl mode by typing '{control} d'. The graph autosaves as 'diagastroHIP96718_2.png'. Save this image onto your PC using:
scp
<abc123>@analysis.astro.ex.ac.uk:/data/shinkley/Keck_Data/completed_stars/DangerZone/astrometry/Jake/HIP96718/diagastroHIP96718_2.png .
Type this into a terminal that is not logged into analysis, it will prompt you to type in your password, then will download the image.

Extension: Photometry

1. Use analysis to determine the approximate positions of the candidate and the star in the images (normally for determining the counts from the star, you will use an image of the star without the coronagraph that has a shorter exposure time).
2. Run cpm_photometry.py and find the exact positions of the candidate and the star respectively using the same method as above.
3. This time input 1 to run photometry when prompted.
4. Input the radius of the aperture when prompted.
5. Input the inner and outer bounds for the annulus surrounding the aperture, the counts within this annulus will be used to generate a median background noise per pixel that will be used to estimate and subtract the noise within the aperture.
6. The output: residual_aperture_sum and total_err are the background subtracted counts within the aperture and the error respectively.
7. Two images are generated too; one is an image of the location of the aperture and the annuli, ensure these are centred on the source and that there are no significant noise sources close to the source. Also outputted is a curve of growth that shows the total cumulative noise within a radius. A curve that flattens at large radii indicates that you have measured all the counts from the source.
8. Find the exposure times in the ds9 header: exposure time = ITIME*COADDS.
9. Convert these counts to candidate absolute magnitude using:
$$m_c = m_s - 2.5\log_{10}\left(\frac{N_c\tau_s}{N_s\tau_c}\right)$$
$$M_c = m_c - 5\log_{10}\left(\frac{D}{10}\right)$$
where; m_c is the candidate apparent magnitude, m_s is the star apparent magnitude for a particular band (obtain from SIMBAD, WISE data), N_c is the counts from the candidate, N_s the counts from the star, τ_s is the exposure time of the stellar image, τ_c the candidate exposure time, D is the distance of the star to earth and M_c is the candidate absolute magnitude.
10. Plot these photometric absolute magnitudes against models for substellar objects, use a range of ages (eg: 100Myr to 5Gry), it is then possible to discard the ages that are far from the candidate's position and then use interpolation to determine mass estimates for the candidate assuming different ages for the system. Excel is a good program to determine the absolute magnitudes and for doing the interpolation.
11. For the models: Use Mark Philip's models for probable planetary objects ($<20M_{Jup}$), use Baraffe 2015 substellar models for brown dwarves and larger objects, links for both sets of models are on the next page.

Baraffe:
http://perso.ens-lyon.fr/isabelle.baraffe/BHAC15dir/
Philips:
https://www.erc-atmo.eu/?page_id=322

Example of resulting colour magnitude diagram:
Red error bars are the photometric position of the candidate