CARDIFF UNIVERSITY

PRIFYSGOL CAERDYDD

1 Methodology

This document covers the data analysis techniques used to produce light curves of supernovae from data obtained on the LCO network. It will introduce the network, discuss the image data format and include a step-by-step guide to data collection and analysis. The codes mentioned within this document can be found here. Provided by: Hayley Barratt-Bentley (2019)

Contents

1.1 Introduction to the Las Cumbres Observatory network

The Las Cumbres Observatory (LCO) global science network observes and researches throughout many areas of astronomy, e.g. Exoplanets, NEOs and Supernovae. [8]

The scope of the network allows the observation of objects which need to be monitored for long periods but also transients which appear suddenly without warning. Being an integral partner in many supernovae surveys, have developed the field significantly[7]. The two collaborative projects which impact on this particular work are ASAS-SN and Gaia.

LCO: The key initiative is the Supernova Key Project which aims to build the world's largest sample of data on local supernovae by observing 500 supernovae in 3 years[4]. This was already achieved within 2 years when they had provided >80,000 images and 2,000 spectra. Currently they monitor 30-40 active supernovae and such rapid response projects allow the community to obtain fast classification of the events. To see more on this project visit: http://adsabs.harvard.edu/abs/2017AAS...22934110H

The LCO network accessible with this project consists of 5 image telescopes, 2 spectrographs and multiple filters as listed below:

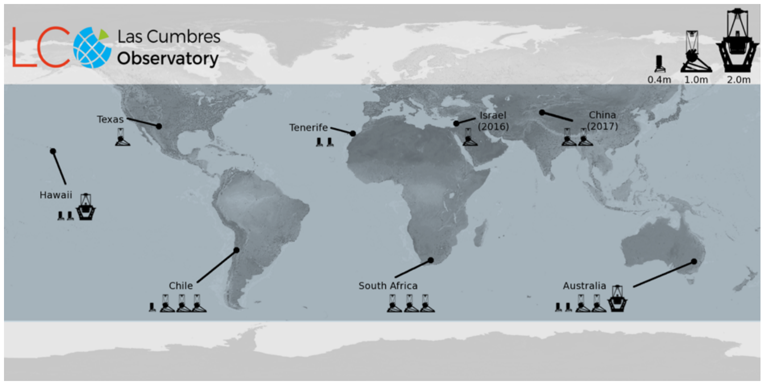


Figure 1: LCO telescope network map[1]

Type	Name	Class	Pixel scale	Field of view	Filter wheel options
Imager	Spectral	2-meter	0.300 (bin 2x2)	10'x10'	18
	Sinistro	1-meter	0.389 (bin 1x1)	26'x26'	21
	SBIG 6303	0.4-meter	0.571 (bin 1x1)	29'x19'	9
	Merope	2-meter	0.278 (bin 2x2)	5'x5'	18
	SBIG	1-meter	0.464 (bin 2x2)	15.6'x15.8'	21
Type	**Name**	**Class**	**Wavelength coverage /nm**	**Resolution**	**Nm per pixel**
Spectrographs	FLOYDS	2-meter	540-1000 / 320-570	400-700	0.35-0.17
	NRES	1-meter	380-860	6x 53000	---

Figure 2: LCO telescope table [2]

To find out more about the filters deployed with each telescope further information is on https://lco.global/observatory/filters/

1.2 FITS format data

Data collected from the LCO network can be downloaded from the portal in the format of a FITS file. FITS file (Flexible Image Transport System) files are an open standard, defining a digital file format making it useful for storage, transmission and processing of data[3].

1.3 Data analysis using Astroimage J

This section will be a brief methodology for how to use Astroimage J to produce light curve data from .fits image files.

1. Ensuring images are fits files, import into astroimage J. Select option “Use virtual stack” to keep all images together and “Sort names numerically” to ensure images would remain in correct order.

2. Images need sorting through, eliminating any blurry or flared image and editing exposure ensuring to “display as image negative” making objects easier to resolve, see figure.

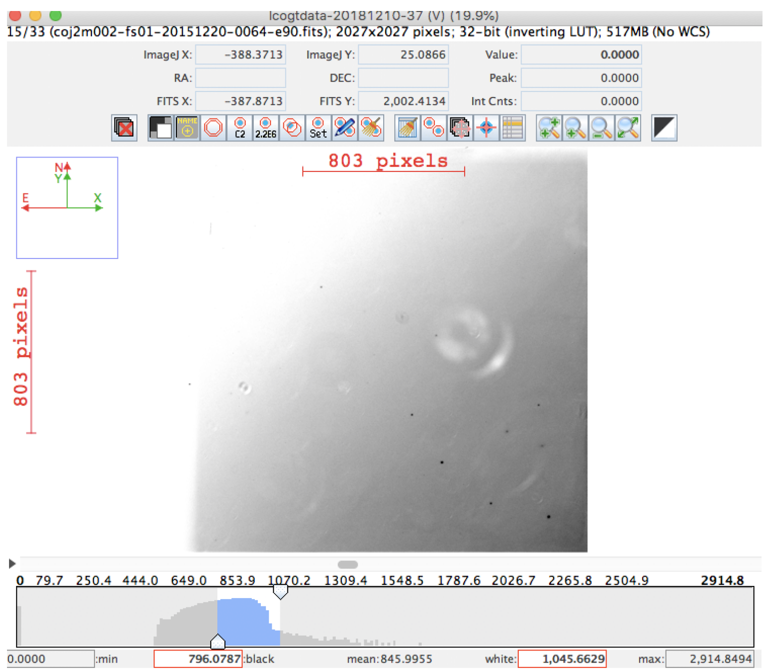


Figure 3: Exemplar image to be discarded due to exposure

3. Images required to be rotated to correct orientation using comparison images from different sources and if not already north facing view, invert Y.

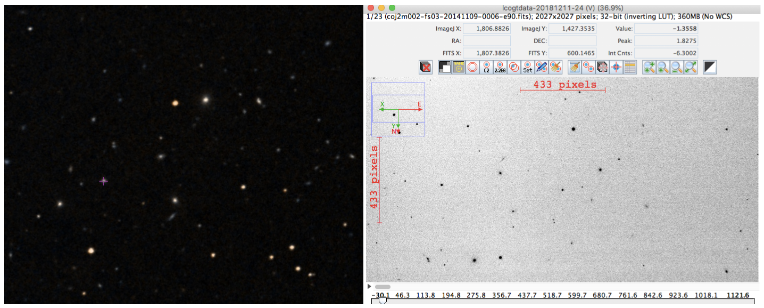


Figure 4: Exemplar image of Gaia alerts data for orientation comparison

4. Brightness and contrast adjustments can be made using bottom scroll bar to get a clearer image, increasing clarity of objects.

5. Observations across multiple different frames are used in order to see a fluctuation of magnitude, any variability measured in the image needed to be analysed. This is to ensure correct variability is measured and is not caused by other factors

6. Ensure to establish multiple comparison stars to ensure correct variability of supernovae observed and evaluate ones which are clear in every image and non-elliptical (more likely to vary themselves). As many suitable variable stars should be chosen and used in the photometry.

7. Aperture radius is determined by area in the image for which the pixels for observed object lay within. Use the straight line tool to draw over the target object horizontally.

8. The Analyse function is used to plot a seeing profile shown below and three values in red on the bottom of the window need to be noted for further photometry.

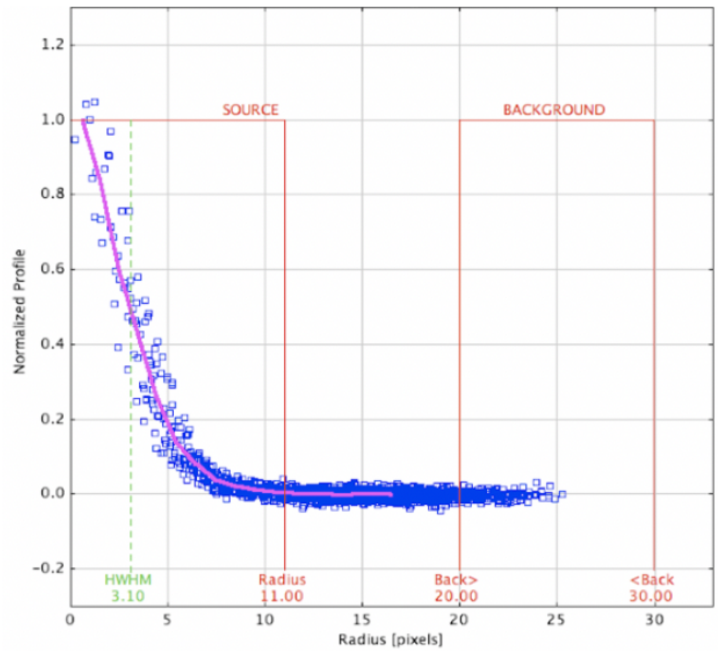


Figure 5: Exemplar image of seeing profile plot from AstroimageJ

9. Multiple aperture function is used, ensuring it is on single step mode, is not using previous apertures and that numbers from the last figure are inputted into: “Radius of object aperture”, “Inner radius of background annulus” and “outer radius of background annulus”, when correct place apertures.

10. Select the main target and follow by selecting comparison stars and finally the enter key. Once all images are analysed save data to a new file.

11. Magnitude can be calculated within said file in excel. Calculated by using ’rel flux T1’ column the function =2.5*log10 (“Data column number”).

12. Plot Julian Date with magnitude putting the y-axis reversed and minimums set to focus on the data.

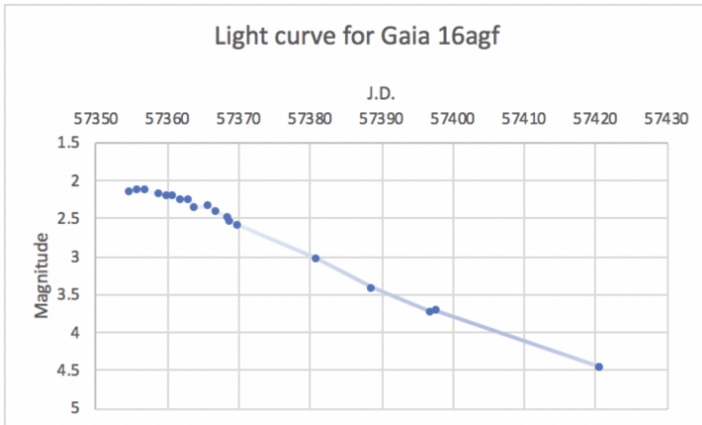


Figure 6: Exemplar light curve plot of Gaia 16agf

1.4 Gaia Alerts and observations through LCO

Gaia alerts index is used to find suitable sources to be observed. Key features that are looked for on the alerts index are the following:

1.4.1 Acting on alerts

- **Appropriate magnitudes:**12-16 magnitudes for ¡2m telescopes, 16-19 for 2m telescopes, no lower than 19. To observe good supernovae light curves, observations need to be made on the initial climb, capturing the peak and watching the magnitudes descent following weeks/months.

- **Historic magnitude:** A useful indicator of how much the object's magnitude has risen and thus showing if it is likely to be a supernova depending on increase in magnitude. A substantial increase in magnitude, but not such an increase miss peak magnitude, is that of 0.5-1 magnitude.

- **Recent observation date:** Observations which cause the alert need to be within the last 48 hours for it to be feasible to capture the beginning of the light curve, initial increase often occurs within 7-14 days.

- **Minimum candidate supernovae:** Within the comment section of the Gaia alerts index there will often be a statement of what the alert is predicted or clarified to be. Within this section the aim is to find candidate or confirmed supernovae.

- **Observability:** Needing to be performed outside the Gaia alerts index, instea using StarALT. The RA and DEC from the observation would be input in along with the location of the telescope proposed to observe from (depending on whether 2,1 or 0.5 m are needed, a larger issue for the 2m). This will then enable visibility to be tracked for the duration of the observation, informing if tracking the object for the next few months and gain a sufficient amount of data is possible.

Throughout use of Gaia alerts[6] it is suggested to monitor the site once every 1/2 days for alerts on suitable supernovae. The flow chart below steps through the decision process when choosing whether to act on an alert.

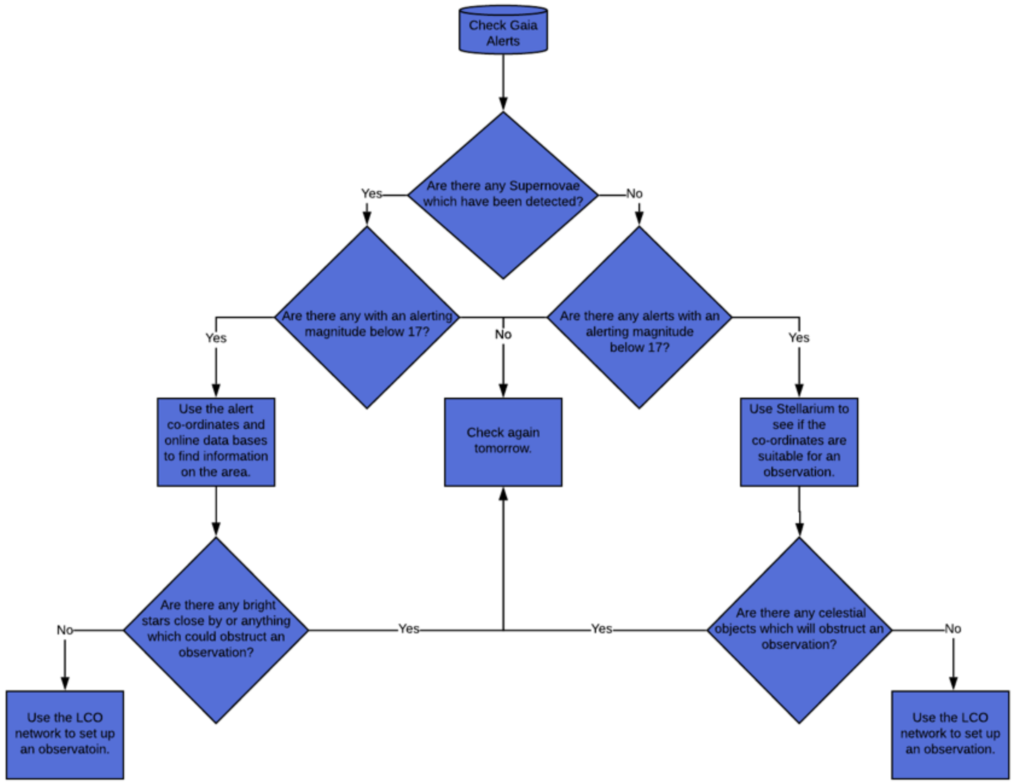


Figure 7: Selection process flow chart.

2 Data analysis

This chapter illustrates the analysis performed on collected data from the LCO network and from the archive data respectively, presenting errors generated within photometry and LCO data on figure plots.

2.1 Image processing post data collection

2.1.1 Funpack

From the submitted observation requests window once an observation has complrted, data can be downloaded in the form of a fits.fz file. To analyse this the file needs to converted, using the terminal (for Mac OS) and the Funpack package, into an average fits file enabling it to be used within AstroimageJ. For Mac OS, once funpack has been downloaded the following should be inputted into the terminal and convert files to .fits format.

cd
cd documents
cd (folder name containing fits.fz files)
f*or image in **
do
funpack -F DOLLARimage
done.

2.2 Las Cumbres observatory (LCO)

The data collected for this project was done through the LCO telescope network, for more depth as to what this network is for and what it contains visit: INTERIM. This network can prove itself to be fairly unreliable, mainly due to the lack of priority behind requests made by undergraduates. Although justified, this can have an impact on the data collection and can also be further impacted by the collapse of telescopes such as the Hawaii telescope in early January 2019. This was due to storms and was not the only telescope to be affected by weather. Thankfully, due to the monitoring system on the LCO webpage, the collapse of a telescope is easy to spot and therefore new requests can be put in on the 1m telescope using a higher exposure to limit data loss.

Telescope availability history

This chart shows the percent of operational science time for each telescope over the last 4 days. View the detailed operational status.

Telescope	-4 days	-3 days	-2 days	-1 day	Today
Siding Spring 0.4m A	100	100	90	100	
Siding Spring 0.4m B	100	100	90	100	
Siding Spring 2m	100	100	90	100	
Siding Spring 1m 1	100	100	90	100	
Siding Spring 1m 2	100	100	90	100	
Sutherland 0.4m A 1	70	72	19	0	
Sutherland 1m 1	70	72	19	0	
Sutherland 1m 2	70	72	19	0	
Sutherland 1m 3	70	72	19	0	
McDonald 1m 1	100	0	17	63	
Cerro Tololo 0.4m A 1	89	92	100	88	
Cerro Tololo 0.4m A 2	91	100	100	88	
Cerro Tololo 1m 2	91	100	100	88	
Cerro Tololo 1m 3	91	100	100	88	
Haleakala 0.4m B	100	100	100	100	
Haleakala 0.4m C	100	100	100	100	
Haleakala 2m	100	100	100	100	
Teide 0.4m A 1	35	100	100	0	
Teide 0.4m B 1	35	100	100	0	
Wise 1m 1	0	0	25	51	

Figure 8: Telescope availability history information table [7]

To combat limited data issues occurring, different steps can be taken during data collection. These steps include:

- Watching telescope availability history shown in figure 5.
- Using longer exposures to ensure when data is collected, objects are resolvable.
- Requesting longer duration observations at more frequent intervals (usually attempting an observation every 72 hours for ∼3 weeks).
- Monitoring data collected and if successful, putting in a second observation as soon as possible.

These steps enable more sufficient data collection with the LCO network.

2.3 Data analysis

This second flow chart steps through the stages of the analysis process, showing all programs and assistive scripts which can be used.

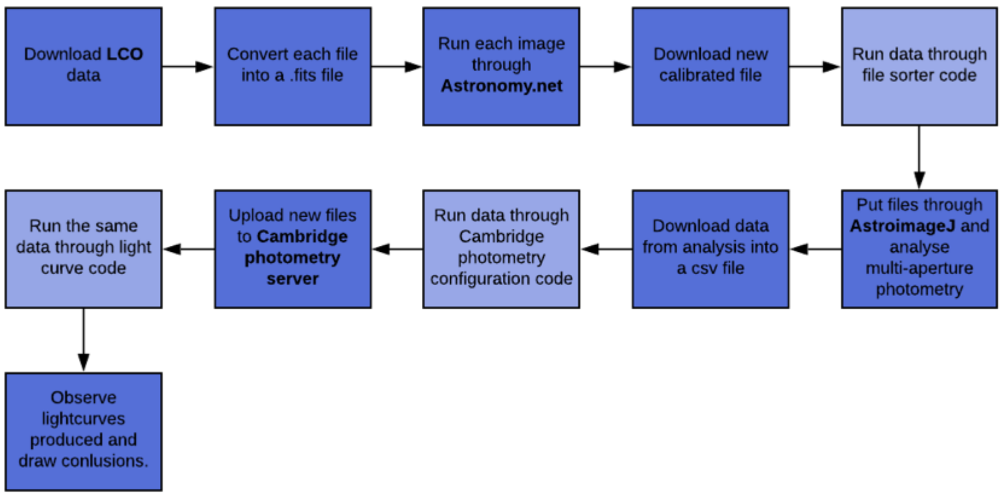


Figure 9: Methodology flowchart, scripts hi-lighted in light blue

This analysis process can be extremely time consuming. For example: to process a single image through Astronomy.net, analyse it through AstroimageJ and then calibrate the data file to upload it to the Cambridge Photometry Server can take approximately 20-30 minutes per frame. Given some data sets collected would be in multiple filters across many time frames, this makes it a strenuous time-consuming process. To help aid this part of the analysis, three algorithms have been developed: An algorithm to sort files , an algorithm to configure files and an algorithm to visualise data. These algorithms were all produced through Python and are reusable for any transient data collection in the future.

2.3.1 File sorter

Although this algorithm may seem trivial, what it solves had the potential to cause multiple issues within data collection. When files are uploaded to Astronomy.net it produces albums such as in figure 9.

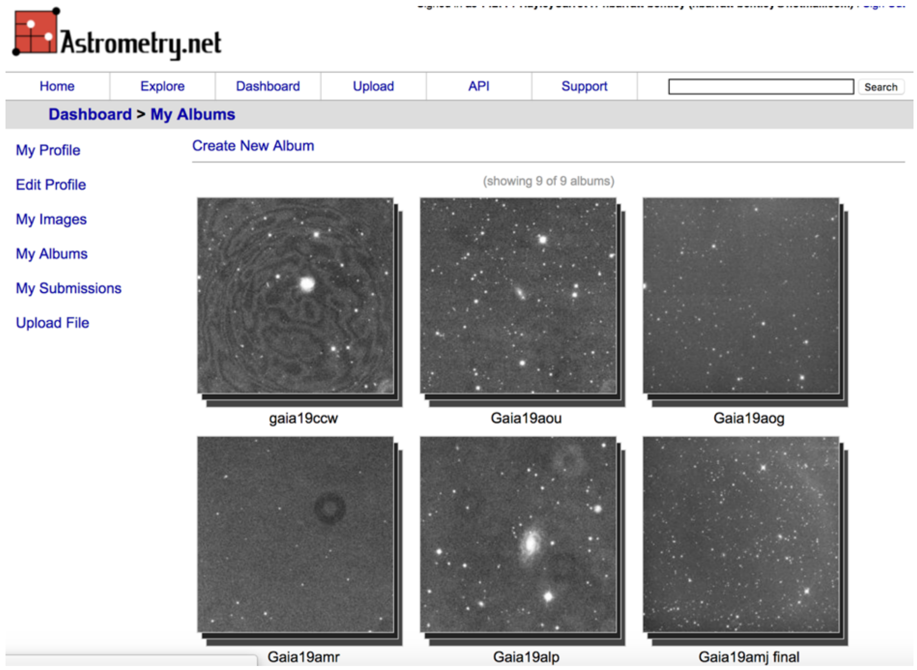


Figure 10: Album format on AstoimageJ.net [8]

There is no available function to download these albums in one step, but instead the system requires the user to download each image individually and outputs the files in the following way:

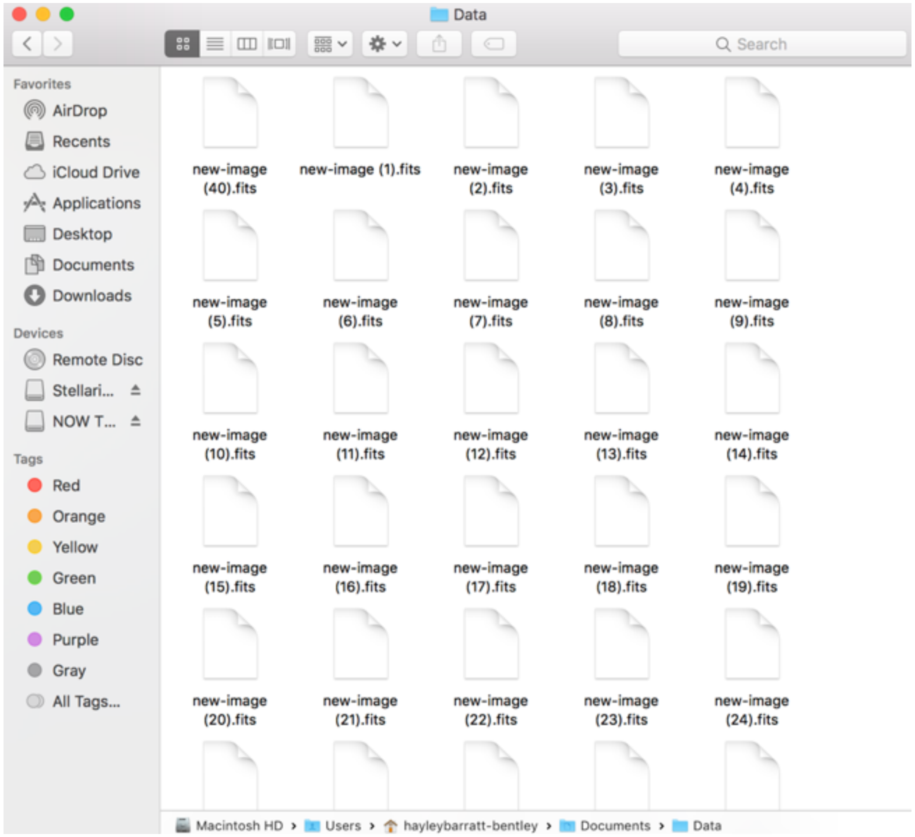


Figure 11: Image naming format once downloaded from Astronomy.net

This algorithm takes inputs from the user of the file location, destination and observable name and then collects all other relevant data from the fits files themselves, resulting in all files being renamed as shown below.

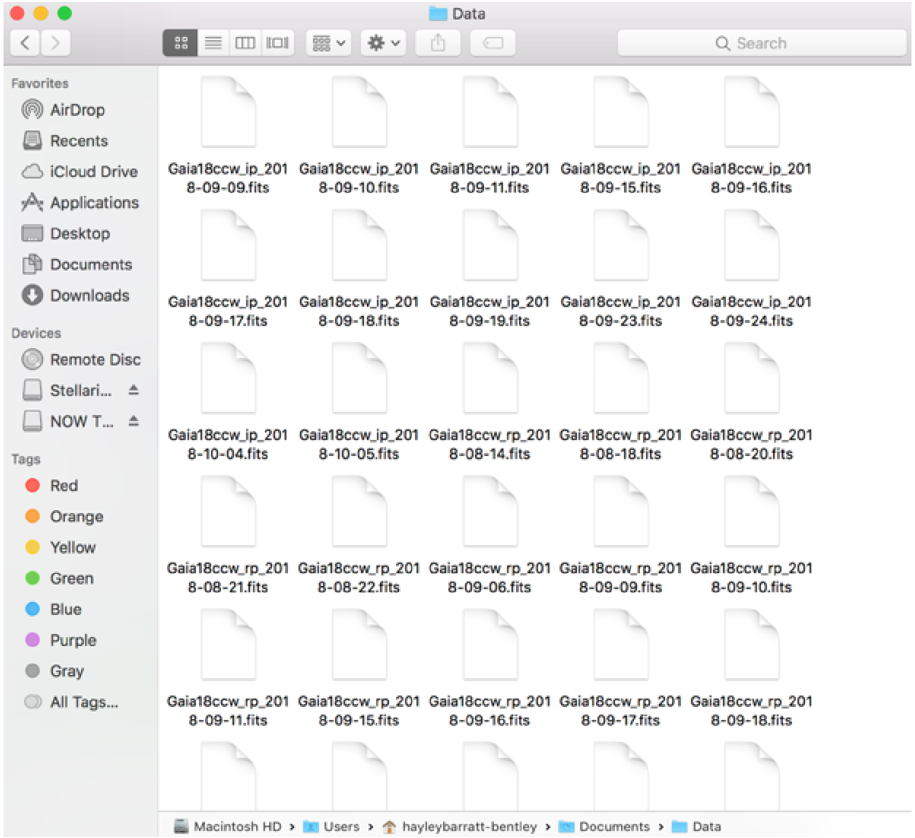


Figure 12: New naming format after processing with file sorter script

This script makes it much easier to process data, ensuring files of different observations, filters etc, do not get mixed together.

2.3.2 Light curve plotter

Similarly, to the previous algorithm, this script relies on inputs from the user. It asks two questions: What is the name of the csv data file? (Collected from Astroimagej multi-aperture photometry see [ref interim]) and What is the name of the object which was observed? These inputs enable the algorithm to find the data file and also to title the graph produced. An example of a graph produced is that done from data collected from an archival supernova, Gaia16agf.

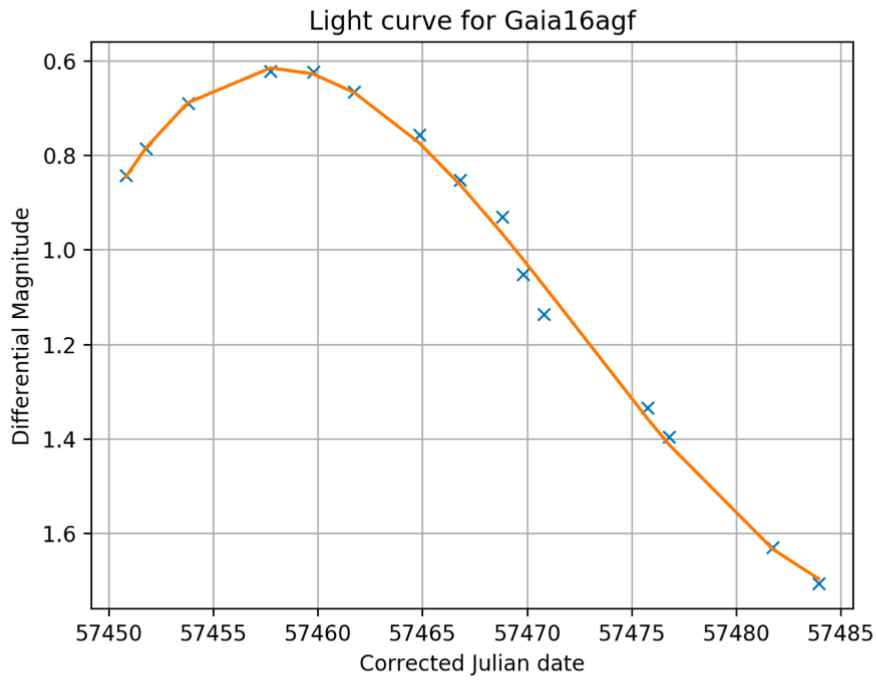


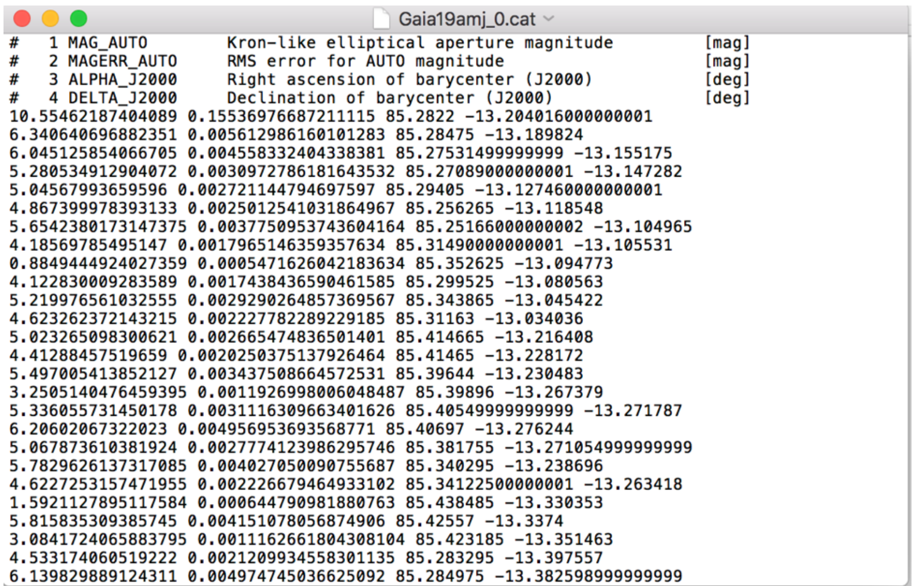
Figure 13: Exemplar graph formed through graph potter, discussed later in the report.

This algorithm works by plotting the corrected Julian date, collected straight from the data file, and then converting the source flux to magnitudes, plotting it at each frame on an inverted y axis. The best fit line is computed using polynomial fitting, polyfit and is fitted at the third order, computing and plotting y axis errors is also performed.

2.3.3 Cambridge calibration algorithm

Previously for this part of the analysis, data files for each time step were being manipulated by hand, through copying and pasting columns of data into a new excel file from the original data file. Due to these data files containing up to 300 columns at times and this having to be done for every frame captured, this was a very inefficient process.

This algorithm again takes inputs from the user for: File name, Name of observed object, Number of filters used. Then it gets all data needed from the AstroimageJ measurement file [] and processes it to the necessary format. There were a number of issues in the creation of this script, as it had to account for user or system mistakes such as: choosing a poor comparison star or selecting the wrong observable. In these cases, it would output null variables for each, making it clear what issue had been made. This algorithm will take a batch of images, for example, 30 images of a transient, all with different filters or time stamps. The algorithm is then able to sort through the data for each time stamp and filter, process the data for: right ascension (RA, in degrees), declination (DEC), magnitude and error in magnitude. New files for each time stamp would then be output into a folder and named using the file's date of observation, filter and object. The output .cat file would be configured as shown below, showing a header followed by magnitude, magnitude error, RA and DEC:


Gaia19amj_0.cat

```
#   1 MAG_AUTO        Kron-like elliptical aperture magnitude         [mag]
#   2 MAGERR_AUTO     RMS error for AUTO magnitude                    [mag]
#   3 ALPHA_J2000     Right ascension of barycenter (J2000)           [deg]
#   4 DELTA_J2000     Declination of barycenter (J2000)               [deg]
10.55462187404089 0.15536976687211115 85.2822 -13.204016000000001
6.340640696882351 0.005612986160101283 85.28475 -13.189824
6.045125854066705 0.004558332404338381 85.27531499999999 -13.155175
5.280534912904072 0.0030972786181643532 85.27089000000001 -13.147282
5.04567993659596 0.002721144794697597 85.29405 -13.127460000000001
4.867399978393133 0.002501254103186967 85.256265 -13.118548
5.6542380173147375 0.0037750953743604164 85.25166000000002 -13.104965
4.18569785495147 0.0017965146359357634 85.31490000000001 -13.105531
0.8849444924027359 0.0005471626042183634 85.352625 -13.094773
4.122830009283589 0.0017438436590461585 85.299525 -13.080563
5.219976561032555 0.0029290264857369567 85.343865 -13.045422
4.623262372143215 0.002227782289229185 85.31163 -13.034036
5.023265098300621 0.002665474836501401 85.414665 -13.216408
4.41288457519659 0.002025037513792646 85.41465 -13.228172
5.497005413852127 0.003437508664572531 85.39644 -13.230483
3.2505140476459395 0.0011926998006048487 85.39896 -13.267379
5.336055731450178 0.0031116309663401626 85.40549999999999 -13.271787
6.20602067322023 0.004956953693568771 85.40697 -13.276244
5.067873610381924 0.0027774123986295746 85.381755 -13.271054999999999
5.7829626137317085 0.0040270500907555687 85.340295 -13.238696
4.6227253157471955 0.0022266794649331002 85.34122500000001 -13.263418
1.5921127895117584 0.0006447909818807 63 85.438485 -13.330353
5.815835309385745 0.004151078056874906 85.42557 -13.3374
3.0841724065883795 0.0011162661804308104 85.423185 -13.351463
4.533174060519222 0.002120993455830113 5 85.283295 -13.397557
6.139829889124311 0.004974745036625092 85.284975 -13.382598999999999
```

Figure 14: Exemplar .cat file produced from calibration algorithm with corrected errors

3 How errors are obtained in AstroimageJ

The following processes for formulating errors were performed through the AstroimageJ system and then manipulated within algorithms designed for this project.

3.1 Reducing errors

This section defines the steps taken using the AstroimageJ software to minimise errors from astronomical surroundings and poor quality frames.

3.1.1 Background interference

In photometry methodology [NTERIM], before multi-aperture photometry is performed the target object is measured to obtain 3 values from the seeing profile. These three values are: object, inner and outer radius. This method reduces errors by removing the background behind the observed object, thus removing any background flux which may cause noise in the data.

3.1.2 Deleting frames

Relatively often in photometry, images are collected which are over-saturated or interfered with e.g. objects occlude the frame causing loss of comparison stars. To reduce these effects, these frames would be deleted before multi-aperture photometry is performed on the dataset. To remove an image from the stack, click the left-most icon on the toolbar. This function only removes the image from current photometry analysis sequence, the .fits file is not deleted from the folder or directory.

3.1.3 Removal of comparison stars

When multi-aperture photometry is complete, it will show a window of all the comparison stars used for the dataset.

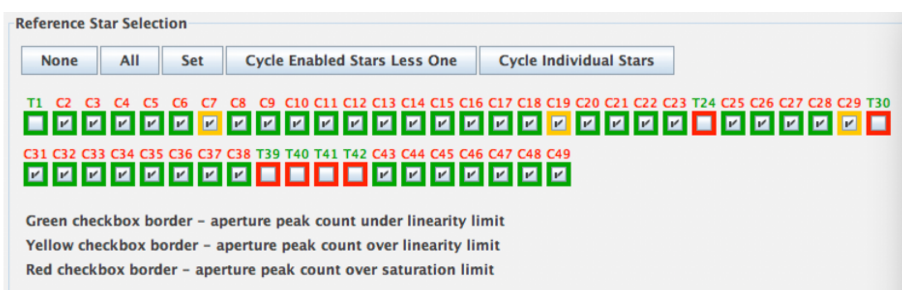


Figure 15: Comparison star data, red indicating over saturation.

This window allows you to unselect any comparison stars which are over saturated, excluding them from the analysis to avoid skewing of the dataset. The data obtained can also be used to detect fluctuation in the comparison stars. This is another reason to remove them from the dataset, they must have a constant flux to be used as a comparison to observe the magnitude in which the target is fluctuating.

4 From Gaia Alerts to Cambridge photometry server

This section will briefly illustrate the process of taking data from Gaia alerts through to the methodology for uploading to the Cambridge Photometry Server.

This report previously discussed methodology for choosing a target, collecting the data and processing it through AstroimageJ, here this will be skipped. However, if the full methodology is required please visit: LINK HERE.

4.1 Using the .cat calibration algorithm

This script requires Python 3.6 to run, if it being used on a later version, modifications may need to be made to suit syntax updates within Python. Once the file is opened, save a copy of the file in the same folder as the measurement files obtained through AstroimageJ photometry.

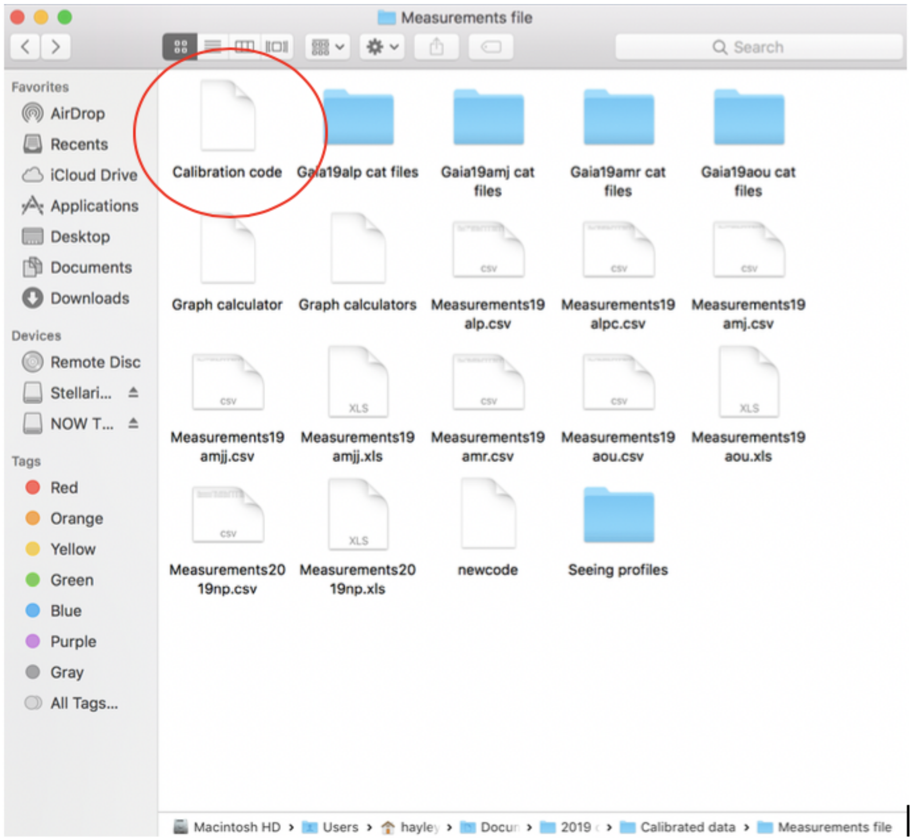


Figure 16: Calibration code necessary file location.

These must be in the same folder for the script to function, If not the whole file path must be written into the script. When the algorithm is run it will ask two questions:

- What is the file name for the .csv data file?
- What is the name of the object observed?

The data must be converted to a .csv file beforehand. This can be done through opening the measurement file in excel and saving it as a Comma Separated Value (.csv) file. The object name will be used in naming the .cat files later on, it is recommended this is written in full detail to prevent confusion.

After running the file there is one main issue likely to occur. If there is an error message displayed showing two arrays having a different length, do the following:

If any of the calibration stars were deselected as shown in figure 15, these have to be manually deleted from the excel file before running the script. This is because upon deselecting them from the dataset, they are renamed. This means when the script calls: `c_data = data.filter(regex='rel_flux_C')` it will not find any which were selected.

Although this sounds beneficial, the algorithm will still be able to find the corresponding error values, thus trying to divide magnitudes by a longer list of error magnitudes later on. For this reason, both stars and corresponding errors for this data must be deleted from the .csv file, prior to running the script.

The algorithm will now output the .cat files, these will be output into the same folder the code and measurement file are in. These labeled as "Gaia XYZ.cat" where X will be the year of the observation, Y will be the corresponding letters for the observation and Z will be the frame number through zero indexing e.g. Gaia19amj_0.cat.

4.2 Uploading to Cambridge Photometry Server

Before uploading to the server, ensure the user has access to either their own personal hashtag or one under the academic team that the user is working with. Once a hashtag is available, log into the server at: Cambridge Photometry Calibration Server Once logged in the user will be shown the following page:

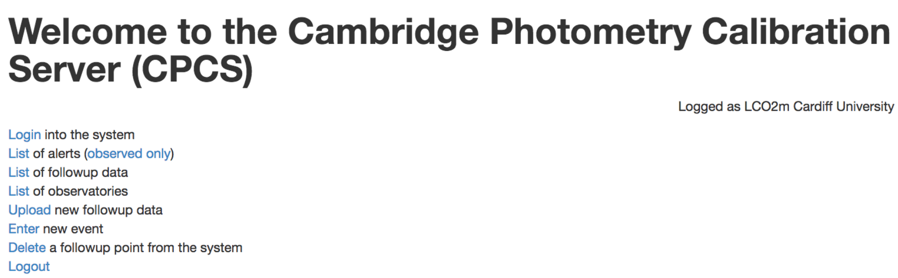


Figure 17: Cambridge Photometry Calibration Sever user page.

The user must now add a new event under the name " ivo://GaiaXY" X and Y holding the same meanings as previously mentioned e.g. "Gaia19amj", the RA and DEC of the target in degrees and the Gaia page for the object, if relevant. This then allows followup data to be added to the event. If this is unsuccessful the user must look through "List of alerts (Observed only)" for the target they're looking for.

Once an event has been made/found the user must then use the Upload function and will be lead to the Follow-up Data Uploading Form:

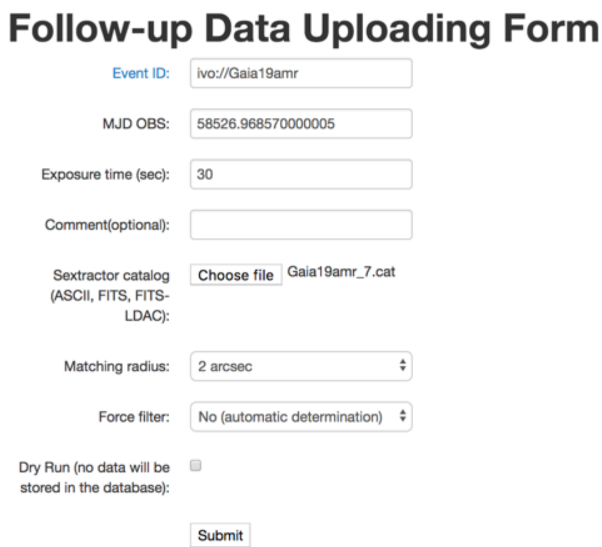


Figure 18: Follow-up Data Uploading Form [9].

The following sections must be filled in, ensuring the correct Modified Julian Date (MJD), which can be found by selecting "Data" in the Python file. This will open up a window which will present the file name and MJD, for exposure look in the "Condensed data" window in the variable explorer.

If the previous file sorter script was used this should display the filter for each image. This will enable the user to use the Force filter setting, ensuring the data uploaded is displayed correctly. Select Dry run to see if the data looks reasonable before allowing a complete submission. To determine sensibility look at errors and scatter.

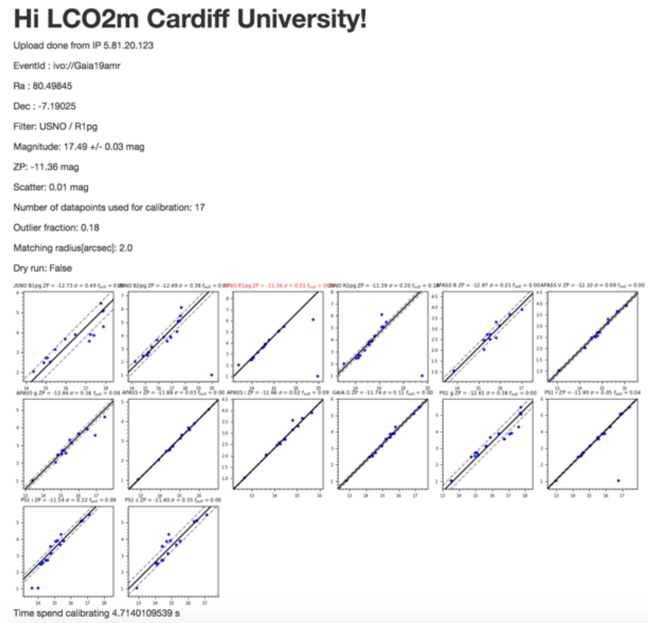


Figure 19: Cambridge Photometry Calibration Server processing page

After submission, the user will be taken to the following page, this will display the number of comparison stars used and the apparent magnitude determined by the system. Once uploaded, the user must wait 10-30 minutes for the data to reach the Gaia follow up server. After this time, the data will be visible to the public and plotted alongside the data retrieved from others and the Gaia system itself. Below shows and example of the follow up figures from this report and it can be found at Gaia19amr follow up page.

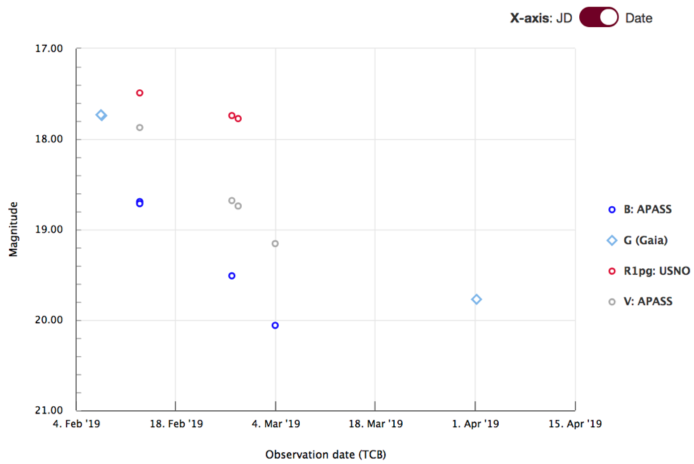


Figure 20: Follow-up Data Uploading Form [9].

4.3 Error calculation

Within the measurement file produced by AstroimageJ, the error is labelled as "Source_Error_" followed by T1 for the target and C1, C2... for any following comparison stars. This data value accounts for Charged Couple Device (CCD) gain, read out noise, dark current, quantisation noise and poisson statistics in the source and sky background signals [10]. The exact equation used to calculate this is:

$$SourceError = \sqrt{IntSourceCnts \times Gain + NSourcePixels \times \left(1.0 + \frac{NSourcePixels}{NSkyPixels}\right) \times (SkyPerPixel \times Gain + DarkPerPixel + RON \times RON + Gain \times Gain \times 0.083521))/Gain}$$

Figure 21: Source error equation [10].

For the relative photometry error calculations (used in .cat file production), the individual source errors are propagated through summations and divisions using standard error propagation techniques, assuming independent variables. This means errors calculated for comparison stars and thus the target objects magnitude, are done so through summing the individual comparison star errors in the measurement table. [10]

$$tot_{C_{err}} = \sqrt{Source\_error\_C1^2 + Source\_error\_C2^2 \ldots + Source\_error\_CN^2}$$

Figure 22: Total comparison star error equation [10].

This enables relative flux errors to be calculated through propagation, via division forming "rel_flux_err_T1", which is the error used for analysis in this report.

$$Magnitude\ error = 2.5 \times \left(\frac{flux\ error}{2.3 \times flux}\right)$$

Figure 23: Relative flux error equation [10].

5 Data analysis

This methodology can be supported by online resources such as:

- Transient name server, to get host galaxies, redshift, discovery magnitude and date.[11]
- The Open Supernova Catalogue, to obtain a graph of collective photometry data.[12]
- Gaia alerts, to obtain alerting magnitude, RA, DEC, alert date and class.[6]
- SIMBAD, to obtain sky images of the object and near-by stars.[13]

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