Precision Photometry with Y24/SEO

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Photometry Introduction

First of all, what is photometry? Photometry is a technique that involves measuring the amount of light, or the flux, coming from a source. It is important to note that there are different kinds of photometry, each with different methodologies. This document will mainly focus on differential (or relative) photometry, with a bit on all-sky photometry.

Differential Photometry

Differential photometry involves calculating the difference in magnitude between two or more sources. This kind of photometry is particularly useful when trying to measure the magnitude of a source with some intrinsically varying magnitude (such as a variable star or supernova), since we can easily isolate this intrinsic variation from other causes of variation, such as atmospheric conditions.

The methodology documented below is intended to calibrate magnitudes on the SDSS photometric system. Since we will deliberately choose a field with stars of known magnitude (using SDSS DR12), this is easily done and does not require the transformation equations that all-sky photometry requires. We will call our source(s) of known magnitude our comparison stars. This is possible because our sources and our comparison stars are in the same field of view, imaged on the same night with the same photometric conditions i.e. the seeing is the same.

All-Sky Photometry

This is not essential to this project, but if you are interested in more kinds of photometry, read on! All-sky photometry is useful in a case where you cannot capture your comparison stars and source(s) of interest in the same image. This may be the case if you cannot obtain a field with your source of interest *and* stars in the SDSS footprint. This photometric calibration is more involved, and there are a number of factors in the transformation equation:

$$g = g_{instrumental} + \alpha(g-r)_{instrumental} + kx$$

Where α = the color term, k = atmospheric absorption (extinction coefficient), x = airmass i.e. the constant $(\alpha(g-r)_{instrumental} + kx)$ that you add to your instrumental magnitude depends on the atmosphere, your filter, your CCD, and your telescope.

Let's look more closely at these terms. You should be able to obtain $g_{instrumental}$ and $(g-r)_{instrumental}$ from your data. We're left with α, k, and x.

- α: color term
    - To find this term, plot delta_g vs. $(g-r)_{instrumental}$. The color term is the slope of this plot. If the plot is a horizontal line, the slope is zero, and you've found that delta_g has no dependence on the color. In other words, the difference between true g and your instrumental g will not vary based on the color.

- In most cases, your slope will not be zero, and blue will have a slightly different offset than red.
- Note: even if you are able to obtain your zeropoint from the same image as your sources, it may be helpful to calculate your color term to see if it is a significant factor

- k: extinction coefficient
  - To find this term, plot delta_g vs. airmass. The slope of this plot is k. Keep in mind that this coefficient is different for every filter.
  - The standard value of k for the middle part of the spectrum is about .2 $\pm$ 10%. This tends to be worse for shorter wavelengths. i.e. the atmosphere is more transparent for red light.
- x: airmass
  - As you point your telescope at different angles in the sky, the atmosphere interferes to varying degrees. The airmass is a measure of the path length through the atmosphere to your telescope. You should be able to figure out this term based on information from the fits header.
  - x = sec (zenith angle)

Project Introduction and Our Methodology

Our project involved developing a methodology for measuring precise magnitudes in the SDSS photometric system. First, we will use a program called Aperture Photometry Tool to measure the amount of light coming from our sources and obtain our instrumental magnitudes. Then, using another program called TOPCAT, we can crossmatch our data with a catalogue of stars with brightness visible both in our field and in SDSS. The overlap between these two gives us our comparison stars, or stars that both have known SDSS magnitudes and are visible in our field. We can then use TOPCAT to find the average offset between our sources and the comparison stars (our zeropoint), allowing us to adjust the instrumental magnitudes of the other sources that are not in SDSS.

The two main programs will will use, Aperture Photometry Tool and TOPCAT, are downloadable online for free. Check out the FAQ on the software websites if you run into issues downloading or opening the programs. This document will go through the process naming files as gprime and rprime filters, but the same process can be applied to other filters.

For this methodology, we will go through the process with a star cluster for convenience, as it is likely there are nearby photometric objects in the SDSS footprint and there are a few other astronomical exercises we can do with this data (such as plotting a color magnitude diagram).

Part 1: APT

1. SDSS frequently does not have data near the center of a star cluster, as the sources are too bright. We therefore want to take an image of our cluster slightly off-center. Cross check your coordinates with SDSS SkyServer to make sure there are many SDSS

photometric objects visible in your field of view. When you are imaging, you should take at least two exposures in both gprime and rprime.

2. Run your gprime fits file through nova.astrometry.net to obtain a new fits file with WCS coordinates. You should download the file titled “new-image.fits” but rename it for your own organization. Repeat for your rprime file.
3. Open APT. Click “Open Image” at the top left and select your new g-band image (with WCS). Click “More Settings” at the bottom of the window and change the model to any model but A. Then, change the magnitude zero point to 25. This is just a guess, we will correct for this later in TOPCAT. Finally, make sure to click “Apply Settings.”
4. Click on a star on the right side of the window, then click the large “Alter” button. You should have two windows, “Elliptical-Aperture Attributes” and “Photometry Major Radii.” With the first, you can adjust the radius of the red circle, and with the second, you can adjust the size of the annulus bound by the green and yellow lines (inner and outer sky radius). Change the Major radius to 5, the Inner-sky radius to 12, and the Outer-sky radius to 17. These are just starting points; you will adjust these in the next step. Click “Apply” to apply your changes. Remember to click “Recompute Photometry” if the button is red. You can close the window that pops up.
    a. The program counts data units within the red circle. It then uses the count within the sky annulus to estimate a sky contribution to the data unit count (method depends on the model, which we will change in the next step). It then subtracts the appropriate amount of counts due to the sky.
    b. You can also fiddle around with the sizes you input. Generally, you want the red circle to cover about 70% of the light. You can check this by clicking “Curve of Growth” or “Aperture Slice.” For “Curve of Growth,” you should see between the green and yellow lines a line converging to an upper value. If the function is decreasing between these lines, it is likely that your sky annulus is too close to the light source and is subtracting too great a value. Similarly, you can use the “Aperture Slice” tool to see how you should adjust your radii.
5. Click “File,” “Clear Photometry File.” (This is particularly important after you’ve already created a source list.) Click “Source List” at the bottom right and check the box to overlay sources on the image. Then click “Create Source List” and change your source detection threshold to 2 and your source minimum number of pixels to 10 to let more data through. We will filter this data further later on, so we want to let more data in at this step. Click “Create Source List” and close the window.
    a. Before creating the source list, we can either uncheck or check the box that disables source de-blending at the bottom of this window. If this box is unchecked, the program attempts to resolve two sources that are close together. Sometimes this leads to worse data, so you can check and uncheck it to see in the right window if it is better or worse.
    b. Also note: the source detection threshold of 2 and minimum number of pixels of 10 are just starting points. You can experiment with these values depending on your image and data.

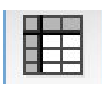
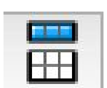
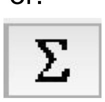
6. We now want to click “Automatically Process Source List.” You may have to wait a few seconds for it to process. We can now close the window and click “List Results,” “Export Contents.” Reset the CSV file name to something convenient and remember to click “Create CSV File.” You now have your source list! You’ll have to go through the same process for your r-band file.
7. If you want, you can at any point go to “APT,” “Preferences,” “Save Preferences” so you don’t have to repeat yourself every time you open the program. Next time, before opening an image, go to “APT,” “Preferences,” “Load Preferences,” and everything should be the same as before.

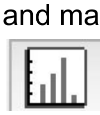
Part 2: TOPCAT

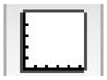
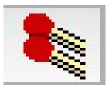
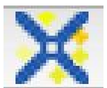
1. Click the File icon on the top left to open your CSV file for your first filter. Make sure you select “CSV” under “Format.” Open a table for each filter.
2. From here, click the icon with two matchsticks (“Create new table by matching rows in two existing tables”) on it. This will create a new table with entries that match based on the criteria you input. In this case, we want sources that are present in both bands. Select your two bands as the two tables and select “CentroidRA” and “CentroidDec” for the RA and Dec columns respectively. Change the match criteria max error to 3.0 arcsec and click “Go.”
    a. This 3 arcsec error is just a starting point. You can and should change it based on your own data.
3. You now want to cross match this combined table with SDSS to obtain the sources that have photometric data in SDSS and are in your images. Click the X icon to the right of the match icon. In the “Remote Table” box, select “SDSS DR9,” and in the “Local Table” box, select the new match table. Select “CentroidRA” (either 1 or 2, it doesn’t matter) under “RA column.” Then select “CentroidDec” under “Dec column.” Change the “Match Parameter” radius to 5 arcsec. Press “Go.” Check to make sure the number of rows (number of sources) you have here makes sense.
    a. Like before, the 5 arcsec parameter is just a starting point. You may want to experiment with this value.
4. Now, you will want to introduce a number of new columns to graph in your new cross match table. Hover over the icons until you find “Display column metadata.” In the new window, click the green plus icon on the top left. You need to create a new column, let’s call it “delta_g.” For the expression, we want the difference between the SDSS magnitude and your measured magnitude. Type the expression with the columns exactly as they are named. In this case, it should be something like “gmag-Magnitude_1.”
5. We can now create a graph using the “Plane plotting window” tool. You can either type in the desired column or select it from the dropdown. Select “gmag” for X and “delta_g” for Y. You should see that most of your points fall on a horizontal line. Now we use the “Add a new function…” button to overlay a potential function. Estimate the best fit and input it into “Function Expression.” You now have what you need to make an adjustment to your initial zero point guess!

6. You should now create a new column for the adjusted g magnitude (“Display column metadata,” green plus). Essentially, you overlaid a function y = delta_g = SDSS Magnitudes - your magnitudes = a constant. We can rearrange to get that the SDSS Magnitudes = Your Magnitudes + a constant (the function you plotted). Name this new column “g_adjusted” or something similar. The expression should be “Magnitude_1 + some number.” Remember that this number can be negative as well.
7. Now repeat steps 4-6 for your r filter. Everything should be the same, replacing “g” with “r” and “Magnitude_1” with “Magnitude_2.” This should all still be in the cross match table. Ultimately, you should have two “adjusted” columns. You can now create an additional column for your g-r color (with your adjusted values, “g_adjusted-r_adjusted”). Make sure to name this so you know it is your values. Create another column for the SDSS g-r values (the expression should be “gmag-rmag”). Create another graph plotting the SDSS g-r values against your g-r values. Add a function with expression “x” to see how close your values are to SDSS.
    a. If at any point your data fits perfectly to the function it’s supposed to look like, something is wrong. Double check to make sure you haven’t plotted something against itself or made mistakes in your expressions.
8. If you’re just seeking to obtain SDSS magnitudes, you’re basically done! You can go back to your original gprime and rprime tables and introduce a new “adjusted” column with the zeropoint you obtained.

Other TOPCAT Tools

-  Table viewer, useful for taking a quick look at your rows, columns, and data. You can also easily create a subset of selected or all-but-selected rows using the two top left icons.
-  Besides adding new columns, you can also check what class each column is. You can use the check all and uncheck all boxes at the top to help reduce the amount of scrolling you do when you select, say, the RA and Dec. Just check the columns that are actually useful to you.
-  This tool allows you to create row subsets. Click the green plus sign and you can set an expression as a condition for this new subset. The expression loosely follows java programming language e.g. you can use “&&” to specify multiple conditions or “||” as “or.”
- 

Display statistics for your table here, including standard deviation, mean, min and max.
-  Create a histogram. This is useful for a quick glance at your data.

-  Plot your data. You can also click “Axes” to flip your axes (useful for plotting magnitudes) or change the range of the axes. Once you have a graph, you can also save your graph in a convenient format using the icon to the left of the question mark at the top. One of the most useful tools is the one labeled “Draw a region on the plot to define a new row subset,” located on the top left of the window. This allows you to use your mouse to draw a region that defines a new subset.
-  Match tool, you can use this to create a new table by matching two already uploaded tables.
-  Cross match tool, you can use this to create a new table by crossing an uploaded table with an online database such as SDSS or SIMBAD.

Precision

For this kind of precision photometry, we ideally hope for better than 2% external precision. As of 9/5/2016, we’ve been consistently achieving better than 5% precision on Y24. If our data has great external precision, then our delta_g values (the difference between our instrumental magnitudes and the SDSS magnitudes) for differing magnitudes should be pretty similar. In other words, the scatter around the line we used to estimate our new zeropoint should be fairly small. To quantify this scatter, we need to calculate the rms (root mean square) to give us an estimate of the error. Luckily, TOPCAT will essentially do this calculation for us. The difficulty lies in justifying a subset selection of your data that you can use to determine a precise zeropoint.

- RMS: for a set of n values $\{x_1, x_2, \ldots, x_n\}$, $x_{rms} = \sqrt{\frac{(x_1^2 + x_2^2 + \ldots + x_n^2)}{n}}$

To take a look at the rms, click the sigma icon, which opens up your statistics. The number under “SD” (standard deviation) is the rms. Look under “delta_g” and convert to percent to get your percent precision in the gprime filter. If you’re looking at your entire range of data, it is likely that this number is quite high. Here are three methods of easily justifying a smaller subset selection.

1. SDSS SQL
   - See the following section. Using the SDSS clean flag is a convenient way to ensure that we select the best subset of data.
2. Limiting MagUncertainty
   - The parameter MagUncertainty is from APT and is likely a good measure of our statistical uncertainty. It is also most likely to be higher for fainter stars, outside of what is feasible for either Y24 or SEO. We can define a new subset that is limited by some MagUncertainty. Use the subset tool to define an expression such as “MagUncertainty_1 < .03.” Ideally, you don’t want to lose too many sources, so check the number of apparent rows. Once your new subset is defined, you can

select it from the "Row Subset" menu and take another look at your statistics. You may need to click the refresh button to update it.

3. Sigma Clipping
   - This technique can potentially justify the elimination of outliers from a subset. Typically, we expect our delta_g distribution to be roughly Gaussian. You can use the histogram tool to confirm this visually. If we can articulate our method in eliminating certain data points in such a way that someone else could reproduce our results, then we our elimination can be justified; we are not simply choosing data that "looks good." One example of an explanation could be to reject data points outside of three sigma (i.e. three standard deviations).

Note: We typically expect that our r filter precision is better than our g (and same with i and so on) because the atmosphere becomes more problematic at shorter wavelengths.

SDSS SQL

SDSS SkyServer has some convenient tools, one of which is the SQL (Structured Query Language) search. You can find it here: http://skyserver.sdss.org/dr12/en/tools/search/sql.aspx
With this, you can request photometric information; for our purposes, we will search for stars within a certain RA and Dec bound. The benefit to using this tool instead of the TOPCAT catalogues is that we can utilize the clean flag, which =0 for dubious sources and =1 for "clean" data.

The basic query format is as follows:

```
select ra, dec, g, r, i
from star
where ra between INSERT RA and INSERT RA and
dec between INSERT DEC and INSERT DEC and
r < 17.5 and clean=1
```

Simply replace the capital letters with your RA and Dec in degrees. You can find coordinates for your field by checking on Skynet and converting to *decimal degrees* (for both RA and Dec) or by using the SDSS Navigate tool. You can also select other information and of course, change the magnitude limitation.

You should save this in CSV format for use in TOPCAT. To be able to see the column headings properly in TOPCAT, open your file in a text editor and remove the "#Table" first line and type "#" before the row that contains your headers, leaving no empty row at the top of the page. Once you open this file in TOPCAT, you can use the match tool instead of the crossmatch tool to create a table to find your zeropoint.

Note: if trying to plot a color magnitude diagram, the following format may be more useful, as it returns radial data, as opposed to rectangular. You only need to fill in for ra, dec, and radius (in arcminutes).

```
select P.ra, P.dec, u, g, r, i, z
from PhotoObj as P, dbo.fGetNearbyObjEq(RA, DEC, RADIUS) as N
where P.objID = N.objID
and P.type = 6
```

Some Notes on Improving Your Data

Most of these notes and suggestions come directly from Professor Rich Kron.

- Internal precision
  - It is important to check the consistency of your data in the same filter in a different exposure. In this sense, you follow the same procedure as that for external precision, replacing the second file with one of the same filter (doesn't matter if the exposure time is the same). We expect this internal precision to be about 2-3%.
- Close stars
  - If you are working in a crowded region, the proximity of other closer stars may affect the measurements of your target stars. You should plot delta_g against the local sky background to see if there is any correlation between large delta_g and high sky.
- Visual check
  - If you can pinpoint individual stars that have abnormally high values for delta_g, see if you can identify them in a fits file and see if anything is obviously causing the poor measurements visually. You can do this by looking up their RA and Dec (or x and y pixel coordinates) in the TOPCAT table and then opening the file in DS9 (or some similar program) and searching for the sources.
- Spatial check
  - Check to see if there is any correlation between spatial position (RA, Dec) and large values of delta_g. You should also compute the radial distance from the center of the image for each star (using the x and y pixel positions) and then plot this against delta_g as well to see if the point spread function varies across the field.
- Flatfields
  - To see if dividing flats will be helpful for your images, you need to take a closer look at the flats themselves. Take a look at the digital numbers for whatever flats you have access to; see if there is a large variation in sensitivity across the field. If this is the case, it will probably be helpful to make use of your flats. Otherwise, if your flats are not stable over time, dividing by them may actually make your image worse. It may also be helpful to try averaging or median-ing your flats or picking the flatfield closest to your observation date.

Resources

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Aperture Photometry Tool, TOPCAT, nova.astrometry.net, SDSS DR12 Navigate Tool, SDSS DR12 SQL Search