Multi-band optical photometry of BASS nuclei

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1 Introduction

1.1 Theoretical Background

1.2 BASS survey

The BAT AGN Spectroscopic Survey (BASS) aims to provide a comprehensive, highly-complete census of the most powerful accreting SMBHs (i.e., AGN) in the local universe. This is achieved by obtaining multi-wavelength observations, in particular optical spectroscopy and broad-band X-ray data, for over 1000 AGN selected in the ultra-hard X-ray regime (∼14-195 keV) by the BAT instrument on board the Neil Gehrels *Swift* Observatory, during its continuing survey of the entire sky. This reliance on ultra-hard X-rays ensures that AGN are selected regardless of amount of obscuration that their radiation field experiences by dusty gas along the line of sight (either circumnuclear or host-galaxy-wide).

The BASS project has already provided reliable measurements of key AGN properties, including BH masses and accretion rates, line-of-sight column densities, and strong emission line diagnostics, for over 600 AGN (BASS/DR1; Koss et al. 2017) drawn from the 70-month catalog of BAT. The present analysis relies on the larger, deeper 105-month BAT catalog, which includes 1632 sources, of which 1189 are AGN (Oh et al. 2018). We note that, unlike some other BASS-related works, our analysis includes beamed AGN (i.e., blazars, FSRQs, etc.) and low galactic latitude sources.

1.3 Our objective

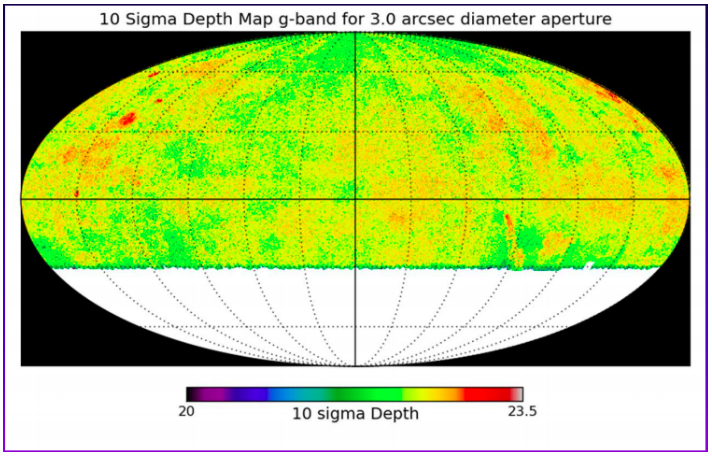
2 The Data

2.1 Pan-STARRS (PS1)

For this project, PS1 catalog is the main catalog. It covers about 75% of the sky (see figure 1). Pan-STARRS is a system for wide-field astronomical imaging developed and it's operated by the Institute for Astronomy at the University of Hawaii[1].

[1]PAN-STARRS website

Figure 1: PS1's 3π sky coverage in g band



The PS1 survey used a 1.8 meter telescope and its 1.4 Gigapixel camera to image the sky in five broadband filters: g (green), r (red), i (near infrared), z (infrared) and y (infrared) (see figure 2). The mean wavelength of the bands is in table 1.

Figure 2: Left: The PS1 capture cross-section in m2/e/photon to produce a detected e− for an incident photon for the six Pan-STARRS1 bandpasses, grizy and w for a standard airmass of 1.2 [1]. Right: Comparisons between the $griz_{P1}$ and other survey filters (CSP = Carnegie Supernova Project and CfAK = CfA-Keplercam, SNLS = Supernova Legacy Survey) [3].

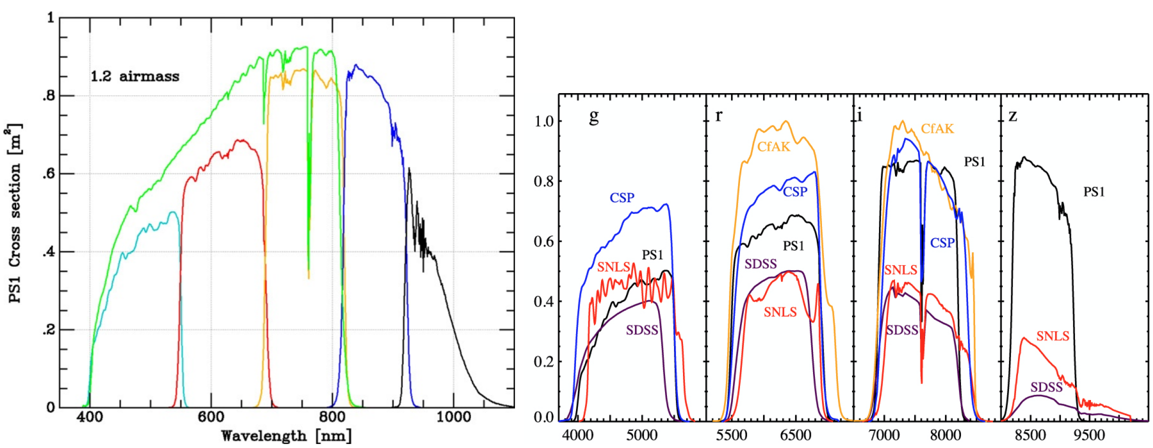


Table 1: The mean wavelnegth of the bands in PS1 and SDSS

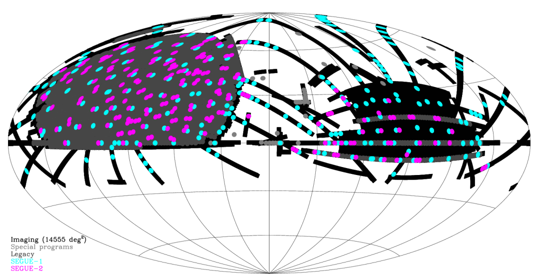
band	mean wavelength PS1 [$\AA$]	mean wavelength SDSS [$\AA$]
u	-	3543
g	4866	4770
r	6215	6231
i	7545	7625
z	8679	9134
y	9633	-

The PS1 survey displays stacks of about 12 warps [2] (or more) per filter. The stacks are astrometrically and photometrically calibrated and have the same zero point (see section 3.1.2 under PS1). The skycell images generated by the Warp process are added together to make deeper, higher signal-to-noise images in the Stack stage. Each stack has an exposure time that depends on the number of warps that are stacked - the exposure time for a stack is given in the FITS header (keyword EXPTIME). It consists of the unweighted sum of the individual warp exposures that were passed to the stacking process. The exposure time is used to convert the PS1 data units to magnitudes (see eq. 2 in section 3.1.2 below).

2.2 SDSS

The Sloan Digital Sky Survey (SDSS) is a major multi-band imaging and spectroscopic survey which uses a dedicated 2.5-m wide-angle optical telescope at Apache Point Observatory in New Mexico, United States. The final imaging data release (DR9) covers over 35% of the sky (see figure 3). SDSS images the sky in 5 broad filters: u (ultraviolet), g (green), r (red), i (near infrared) and z (infrared)[2]. The mean wavelength of the bands is in table 1.

Figure 3: DR12 imaging and optical spectroscopic coverage in Equatorial coordinates (plot centered at RA = 6h, or 90 deg).



3 Measurements - Aperture Photometry

3.1 Calculating Photometry

Given a fits file and the celestial coordinates of a celestial object (star, galaxy or anything that emits enough light) that is seen in the fits file image, calculating this object's photometry is rather simple. The fits file gives the information of the "counts" of each pixel in the image, so to calculate the object's brightness one needs to choose an aperture (preferably as close to the object as possible) and sum the

[2]SDSS filters

“counts” of the pixels that are within the aperture. In practice we had to deal with some complexity that will be decribed in the next few sections, as well as our solutions to these problems. The measured flux of an object, in the native units of the fits image file, will be denoted as DN.

3.1.1 Aperture Photometry package for python

Most of the calculating work is done by the Photutils package[3] that is designed to calculate photometry, when given a fits file, celestial coordinates and an aperture radius. The package calculate an object’s DN in data units and give a more accurate result than simply summing up pixel values. This is becuase when summing up pixels we don’t sum up light within a circle, so a more complcated calculation is requierd here.

3.1.2 Units

The value, or “counts”, of each pixel varies between surveys. We want to find the photometry values in magnitudes, so for each survey we use a different convertion.

- SDSS - an SDSS fits file counts are in nanomaggy (nMgy) units. A "maggy" is the flux density f_ν of the (singel pixel) source relative to the standard source f_0 (which defines the zeropoint of the magnitude scale). The convertion from nMgy to AB magnitudes is the following [4]:

$$m_{AB} = -2.5log_{10}(DN \times 10^{-9}) \tag{1}$$

- PS1 - for the convertion from PS1 data units to magnitudes we use the zero point, which is the magnitude of an object with a count rate of 1. PS1’s zero point is normalized and equals 25 for all the fits files, so the convertion from data units to magnitudes is the following [5]:

$$m_{AB} = -2.5log_{10}DN + 25 + 2.5log_{10}(t_{exp}) \tag{2}$$

  where t_{exp} is the exposure time for a stack in seconds, and it is given in the fits file header under ’EXPTIME’.

3.1.3 Celestial-units to Pixels

Given a fits file and an object’s celectial coordinates, we want to be able to convert distances from sky units (arcsec) to pixels in the fits image, so if we choose an aperture radius in arc seconds, we can find the aperture radius in pixels. The details of this convertion vary between the two survey data products:

- PS1 - the convertion is the following:

$$arcsec = \frac{1}{3600 \cdot CDELT1} \tag{3}$$

  Where CDELT1 is the ratio of degrees to pixel in each fits file, and it can be found in the header under ’CDELT1’.

- SDSS - the convertion is the following:

$$arcsec = \frac{1}{\sqrt{(CD1\_2 \cdot 3600)^2 + (CD2\_2 \cdot 3600)^2}} \tag{4}$$

  Where CD1_2 and CD2_2 are RA and DEC degrees per row pixel, and they can be found in the header under ’CD1_2’ and ’CD2_2’.

[3] Aperture Photometry in Photutils

Later we can use this covertion to convert the aperture radius to calculate the background, as described in the next section.

3.1.4 Background

An important part of calculating photometry, is subtructing the image's background from the source counts, since the sky and unresolved emission can create background light, and there might be another light emitter close to the object (or in front of it) that can add light to the DN. To calculate the background we set 3 radii: small, medium and large, such that $radii = [r, 2r, 3r]$, where r is the aperture radius used for the source measurment. The background is calculated in the ring between medium and large radii (the big ring), since between the small and the medium radii some light from the object might be present. To sum pixels within a circular aperture, where (x,y) is the location of the object in pixels, the pixels that are added to the sum are the ones within [x-3r, x+3r] and [y-3r, y+3r] and also where their distance from (x,y) is in the range [2r, 3r]. Here we denote DN as the set of count values that are within the big ring. The background is calculated using:

$$bg = median(x_{bg}) \tag{5}$$

where x_{bg} is the set of count values in the big ring. The background uncertainty is:

$$\Delta bg = \frac{SDT(x_{bg})}{\sqrt{n}} \tag{6}$$

where n is the number of pixels in the big ring. In the calculation of the uncertainty I neglect the poisson distribution uncertainty, since the statistical uncertainty (as we saw in our measurments) is the dominent one. Equations 5 and 6 give as the median and the uncertainty of the background in one pixel, so to calculate the background subtracted source counts:

$$DN_{cor} = DN - bg \cdot \pi r^2 \tag{7}$$

To find the total background uncertainty we multiply the uncertainty by the circle area:

$$\Delta bg_{tot} = bg_{err} \cdot \pi r^2 \tag{8}$$

3.1.5 uncertainties

An important factor we need to address here is the gain: in CCD imaging, gain refers to the amplification a given system will produce [6]. The DN is calculated using:

$$DN = \frac{electrons}{gain} \tag{9}$$

where electrons is the number of electrons that encountered the measuring instrument. We can find the gain of every image in the fits file header: in PS1 it's under 'HIERARCH CELL.GAIN' and in SDSS it's under 'NMGY' (NMGY is $\frac{1}{gain}$ so for SDSS $DN = NMGY \cdot electrons$). The gain is important when calculating the uncertainties, since we know that the electron counts follow a poisson distribution, but we need to find the uncertainties for DN. The DN's inaccuracy consists of 2 quantities: the poisson distribution uncertainty of the electron count and the uncertainty in background determination. The poisson distribution uncertainty we calculate with:

$$\Delta pois = \frac{1}{gain}\sqrt{DN \cdot gain} = \sqrt{\frac{DN}{gain}} \tag{10}$$

And the background inaccuracy is calculated in equation 8. We therefore find the total inaccuracy:

$$\Delta DN = \sqrt{\Delta pois^2 + \Delta bg_{tot}^2} \tag{11}$$

The final step in calculating the uncertainties is converting them to magnitudes. Due to the logarithmic nature of the DN-to-mag convertion, the uncertainties are not symmetric, so we get 2 different uncertainties when converting to magnitude: up and down. We denote $Mag(val)$ as the convertion of val to magnitudes, using eq. 1 and 2. The uncertainties are calculated with:

$$\Delta_- = |Mag(DN_{cor} + \Delta DN) - Mag(DN_{cor})| \tag{12}$$

$$\Delta_+ = |Mag(DN_{cor} - \Delta DN) - Mag(DN_{cor}) \tag{13}$$

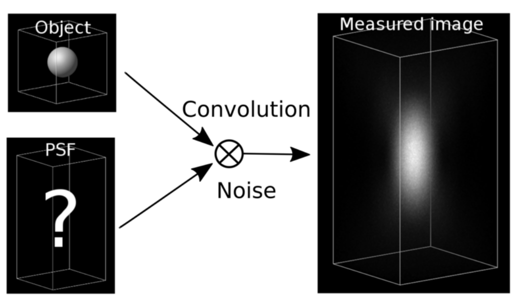
Where Δ_- is the down inaccuracy and Δ_+ is the up inaccuracy, both in magnitudes. The uncertainty range is $[DN_{cor} - \Delta_-, DN_{cor} + \Delta_+]$.

3.1.6 concederations in choosing Aperture Radius

To choose the aperture radius correctly we need to understand PSF. The PSF - point spread function - of an optical device is the image of a single point object (see figure 4). the PSF is an atrribute of the optical instrument used to capture images, so the degree of spreading (blurring) in the image of this point object is a measure for the quality of an optical system. The PSF causes the point object to spread to an elliptical shape, but the sum of light from the object is conserved (though we need to change the aperture to capture all of it). To try and capture the light from the spread object, we can use the PSF's FWHM (full-width-half-maximum) as the aperture radius. Since the object is elliptical, we have 2 FWHMs - major axis and minor axis - we will use their average as the aperture radius. In a 2-D gaussian, $FWHM \approx 2.355\sigma$, so the percentage of area under the gaussian that is bounded by the FWHM is about 93.75% (when assuming the PSF is a 2D circular gaussian) . Therefore, to find the sum of the light count within 1 PSF, we can use the FWHM as the aperture radius, and then divide the result by 0.9375.

For SDSS images the aperture radius is 1.5 arcsec. For PS1 images the aperure radius is calculated using PS1 catalog information, and this is covered in section 3.2 - **Testing and Statistics - PS1.**

Figure 4: A discription of the PSF's influnce on an image of a point object



3.2 Testing - PS1

During the writing of the program, I did all the calculations on some carefully selected stars (instead of galaxies). This is because stars are effectively a point source of light, whereas the light from galaxies tends to be spatially resolved. I used the SDSS image tool [4] to select 48 stars that have fits files and are visible in all 5 bands. After choosing the stars I uploaded their coordinates to the PS1 Catalog Search[5]. This search can give us information on wether a star is seen in PS1 (as described above) and it can give us the stars' photometry according to PS1 and how it was calculated. This is a very important tool that can be used to test our code, since we can compare our results to PS1's results. We noticed the PS1 search output provides information on two options to calculate the photometry:

1. For each object and in each band, the FWHMs of the major and minor axis of the PSF are given. We can use the average of the two as the aperture radius for the measurment and scale the result by 0.9375, since the FWHM PSF captures only 93.75% of the object's light.

2. For each object and in each band, the aperture radius and aperture filling factor used by PS1 are given. We can use the apreture radius as radius for the measerment and divide the result by the aperture filling factor (now the fraction of light captured within the aperture radius varies).

I've tried both calculations to see which one has a result closer to the PS1 calculated photometry, and found that the best option is the second one - using the filling factor. This desicion was made after comparing the differences between PS1 calculated photometry and my calculated photomotry (hereinafter will be refferd as "the difference"), for both options. For the first option, the median of the differences per band is at most $\backsim$ 0.48 magnitudes (see table 2a), whereas for the second option it's at most $\backsim$ 0.082 magnitudes (see table 2b). There were 2 extreme data points in the difference for option 1 (~2 magnitudes) so the rightmost column in table 2a shows the STD after clipping those data points (the median stayed almost the same, of course).

Table 2: The medians and and standart deviations of the differences in each band for the 48 selected stars using the two options for aperture radii (option 1- PSF radius, option 2 - aperture radion with filling factor)

(a) Option 1

Band	Median	STD	Median after slicing	STD after slicing	Median after clipping	STD after clipping
g	-0.32	0.24	-0.33	0.22	-0.32	0.04
r	-0.32	0.22	-0.32	0.18	-0.32	0.07
i	-0.34	0.43	-0.34	0.47	-0.34	0.07
z	-0.37	0.47	-0.37	0.49	-0.37	0.06
y	-0.48	0.51	-0.48	0.53	-0.48	0.075

(b) option 2

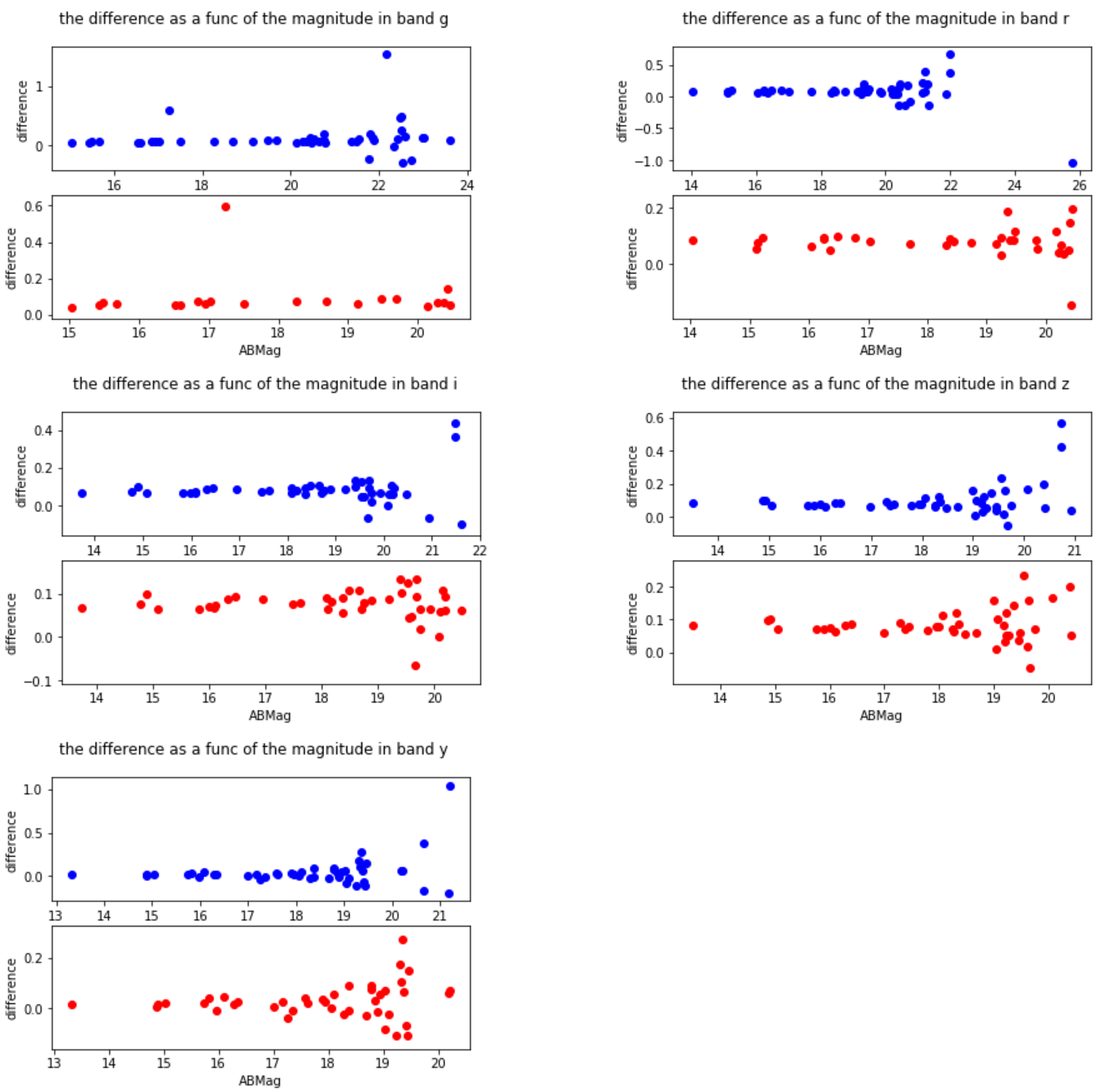
Band	Median	STD	Median after slicing	STD after slicing
g	0.071	0.256	0.063	0.122
r	0.082	0.150	0.080	0.064
i	0.077	0.244	0.075	0.243
z	0.077	0.210	0.075	0.198
y	0.020	0.343	0.021	0.347

In an effort to further understand (and minimize) the differnce, I created a plot of the difference between the measures as a function of the measured magnitude, for option 2 (see figure 5, blue). We noticed that the difference grows significantly for stars fainter than ~20-21 magnitudes. This is

[4] SDSS images tool
[5] PS1 catalog search

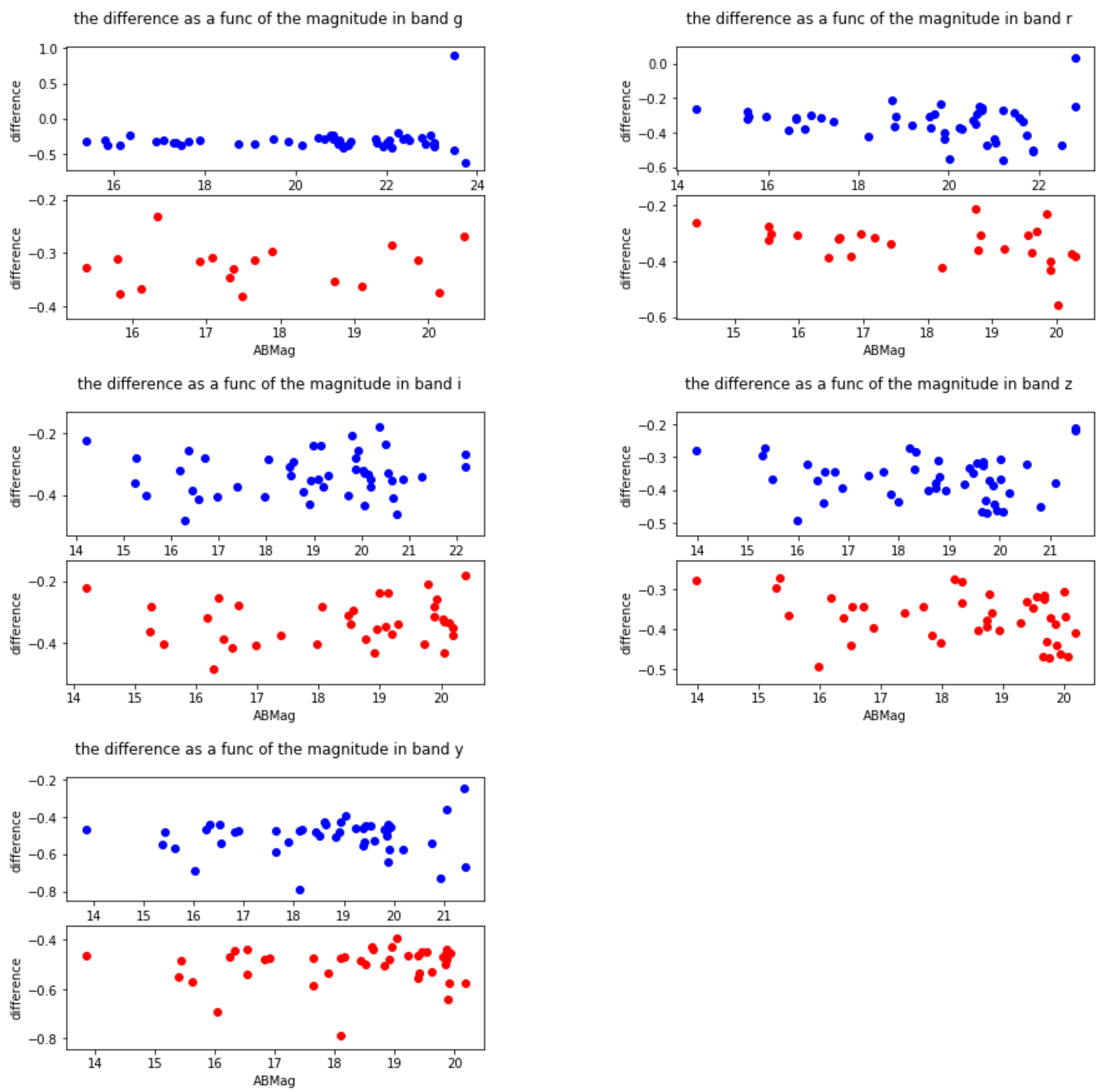
expected since the uncertainty grows for fainter objects. To minimize the effect of this trend on my test statistics, I sliced all the measurments in each band that have a value higher than 20.5 magnitudes (see figure 5, red). We can notice that after slicing, the plots show an approximately straight line constatnt and very close to 0 (in some bands exists a small shift above 0, e.g. band r), so the differences are small enough. The median and STD after slicing are also shown in table 2 (2 rightmost columns). We can notice that for option 1 the values after slicing barely change, whereas for option 2 there is a more significant change (between 2.5%-12%).

Figure 5: The diffrence as a function of the measured magnitude per band in option 2. In blue - before slicing, in red - after slicing.



To see the reason for the values in option 1 to stay the same after clipping, I created the same plots for option 1 as well (see figure 6). We can see the values of the differences are independent of the magnitude and are also approximately a staight line (though they have bigger shift than option 2). Note that the images in figure 6 show the difference after cliiping the 2 problematic data points.

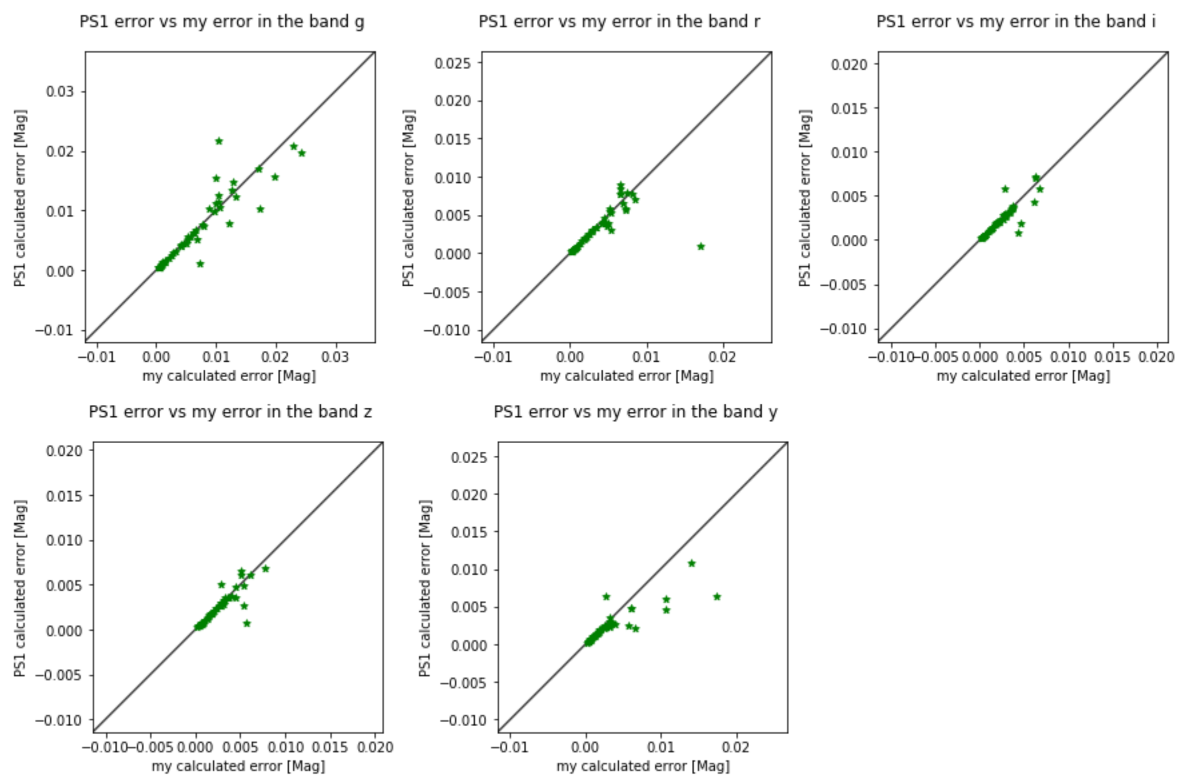
Figure 6: The diffrence as a function of the measured magnitude per band in option 1. In blue - before slicing, in red - after slicing.



After analyzing all the data shwon in table 2 and figures 5-6, we have decided to use option 2 to measure the photometry in the PS1 survey data, so from now on I will reffer only to option 2 in the data and plots. The meaning of a 0.08 Mag difference between the calculation is an approximately 8% difference in flux measurment, so we can conclude that for the measurment of objects brighter than 20.5 magnitudes, my calculations are reliable.

The next step was to make sure that the calculated uncertainties agree with PS1's calculated uncertainties (in PS1's data the uncertainties that match option 2 are under "ApMagErr"), so I created a plot of PS1's calculated uncertainties vs. my calculated uncertainties for each band after the slicing the faint objects (see figure 7). In each panel there's a black line, representing $y = x$, to have a better view on the differences between the uncertainties. We can see that most of the points in the plots are either on or very close to the black line, showing us that not only the uncertainties are of the same order of magnitude, but are also very close to each other, confirming our uncertainties calculation for objects with measurments of up to 20.5 magnitudes.

Figure 7: PS1's calculated uncertainties vs. my calculated uncertainties



4 Results

5 Summary & Conlusions

References

[1] PS1 filter properties from STScI

[2] PS1 wrap images from STScI

[3] The mean wavelength of the SDSS filters from SkyServer/SDSS

[4] Convertion from nMgy to AB magnitude in the SDSS3 website

[5] PS1 data unita to magnitude conversion from STScI

[6] Gain in CCD imagimg, Teledyne Photometrics