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August 11, 2019

Dr. Eugene A. Magnier
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Title: Pan-STARRS Pixel Analysis : Source Detection and Characterization

Dear Dr. Magnier,

I have received the referee's report on your above submission to The Astrophysical Journal Supplement Series, and appended it below. As you will see, the referee thinks that your manuscript is interesting and that it will merit publication once you have addressed the issues raised in the report.

When you resubmit the manuscript, please include a detailed cover letter containing the (mandatory) listing of the changes you've made to the text and your responses to the report. You may upload the list of changes as a file or add it to the text box.

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Reviewers find it helpful if the changes in the text of the manuscript are easily distinguishable from the rest of the text. Therefore we ask you to print changes in bold face. The highlighting can be removed easily after the review.

The AAS Journals have adopted a policy that manuscript files become inactive, and are considered to have been withdrawn, six months after the most recent referee's report goes to the authors, provided a revised version has not been received by that time.

If you have any questions, feel free to contact me.

Sincerely,

Dr. Steven Crawford
AAS Scientific Editor

Referee Report

Reviewer's Comments:

This is an important piece of work to be published as the last of a set of seven papers describing the Pan-STARRS-1 survey and data release 1. It represents a substantial body of work over many years. There are no major revisions requested, but there are quite a number of suggestions to further improve the clarity of the presentation.

The authors could present early in the paper that the goals of the accuracy for photometry and astrometry of stars has indeed been achieved, with quantitative estimates of the accuracy as presented in other PS1 papers, or even by others is comparisons to external data sets.

For many of the sections, the reader would benefit by starting with more of a description of the intention of the algorithms described.

For example:

- Section 4.1: The initial source detection is appears intended is identify bright point sources and omit extended sources. That should be stated, along with the goal of providing sources for the PSF modeling.
- Section 4.4.3: The purpose of the moments is to identify problematic sources and to measure Kron magnitudes. The importance of the Kron fits isn't revealed until much later in Sec 4.6.5 in determining the classification of sources. This importance of Kron fits should therefore be described much earlier, and the rationale for using this for classification since it is typically a noisy measure.
- Section 5: The extended source photometry has not been motivated and it is unclear what the goals are for those objects.

The text doesn't explain how in general bad (saturated, light traps, masked) pixels are treated in the image. Presumably, these must be replaced with some value to allow measurements of some if not all of the source properties described in the paper. The large number of bad pixels is a motivation for all of the averaged quantities in Section 6, so it should be presented what fraction of pixels are compromised and what fraction of objects are compromised in individual images.

The paper should identify which of these measurements and tabulated mask values appear in the DR1 and DR2 data releases. For example, Tables 1-4 must refer to some named quantities in the data releases. This paper should also clearly indicate which quantities are recommended to be most reliable for point source astrometry, fluxes and colors. (My guess would be the astrometry from the stacked images in Sec 4.7, since those aren't recomputed; fluxes from the averaged forced photometry in Sec 6; and colors from either aperture photometry on the stacked images or from the averaged forced photometry, and the authors must know which is demonstrated to be more reliable). The paper should state the same for galaxy astrometry, fluxes and colors.

A detail of the code is presented (variable names, etc) that imply that the code would be publicly available. Is it, and if so where?

The other PS1 papers are discussed in the introduction, but not otherwise referenced throughout the paper. Some notable places where references to these other papers in the series should be made:

- Sec 5.5, where the typical stellar detection limits are quoted
- Sec 6, which of these averaged photometry measurements are used in the PS1 global photometry solution, and which papers demonstrate that the photometric goals are achieved
- Sec 7, where the image differencing detections and photometry is used

A handful of places use lower-case "psf" (Table 2 and pg 13) and should be written "PSF" for consistency. "chi-square" is used both lower-case and upper-case.

A number of places refer to starting guesses for ML minimizations (search for "guess" in the text to find these). It would be useful to provide the formulae for these initializations (and potentially necessary if one were want to repeat the fits).

Although this paper is primarily meant to present the decisions made in the calculations presented in the PS1 catalogs, the authors should

consider including a section about any different choices were they to start such an effort in the future. There are a few places within the text where they allude to such things, but collecting these thoughts in one place would be a useful service.

Abstract:

- This abstract states this is the version used for the "first public release" of the data, but the text says this was used for both DR1 and DR2. Suggest explicitly stating this was used for Data Releases 1 and 2.

Intro:

- "...and include an improved calibration of the PV3"
Please specify if this is limited to the photometric calibration, or astrometry or any other parameters as well.
- Intro should state that this analysis is applied to individual images, image stacks, and image differences (if true), and if the Medium Deep Field program makes use of the same code.

Sec 2:

- For the photometric accuracy goal, it's not stated here whether the 1% number is absolute or relative. Presumably, it's the relative photometry requirement that would be applicable to this work. (This is repeated in Sec 3.)
- IPP should be defined at first mention.
- "CHIP analysis stage" is mentioned without definition.
- For all of the "psphot" variants described, it would be of interest whether the various input images are required to be pixel-aligned.
- Single-epoch images and stacked images should be explicitly defined here (not just the code that acts on them). There are some instances later that refer to "CAMERA", "CHIP" and "STACK" (upper-case), and common terminology should be used throughout. The usage of "CAMERA" and "CHIP" seem to be the same, but maybe they aren't?

Sec 3:

- The overall design goals aren't stated: fluxes and positions for stars; fluxes and positions and shape parameters for galaxies suitably for weak lensing measurements; detection and measurements of transient sources for use by the Moving Object Pipeline for asteroids and supernovae.
- The astrometry and photometry goals are likely written for stars, not galaxies. It should be explicitly stated the quantitative goals are for the contributions to the errors beyond the statistical errors (it looks like you disfavor the term systematic errors?)
- "astrometric accuracy goal" -> "relative astrometric accuracy goal"
- "requirement" -> "goal" to be consistent with the text elsewhere

Sec 4:

- As a reader, I found it confusing to keep track of which measurements are only being made on the brightest 20-sigma sources, vs. the fainter 5-sigma sources. For example, Sec 4.6.5 discussing doing fits to "all sources", but I think this might still only be to the 20-sigma detections? Consider splitting this Sec 4 into two sections, one with all the subsections applying to bright sources, and another addressing all (==faint) sources.

Sec 4.1:

- This overview describes the PSF model class as being defined in step 3, but reading the text it appears that a set of PSF models are determined there and it is only during the faint source analysis (see very end of Sec 4.8) that the PSF model for an image is actually selected.

Sec 4.3:

- It would be of interest to state whether the convention is used for the images to be in units of ADU, electrons, or some other physical unit (albeit only approximately, owing to flat-fielding, etc).
- Table 3 needs to be explicitly referenced in the 2nd paragraph.

- Superpixels are defined in this section as something used for the sky fitting, but in fact are used in other contexts, so it would be good to define it as such and also state the typical physical scale.
- The sky fitting scale length of 400 pixels should be expressed in arcsec as well, and some discussion for the trade-offs in this choice. Are there any instrumental effects (ie, vignetting gradients) effecting this choice, or only sky and astrophysical?
- There must be an estimate of the accuracy of the mean sky heuristic, perhaps as just the step-function-difference of when the more complex measure is used.

Sec 4.4.1:

- For those readers unaware, the first paragraph could explain that in the limit of a Gaussian PSF and isolated sources, this is the optimal detection algorithm. Then the choice of approximating the PSF by a Gaussian for the convolution is presumably to allow the fast computation by having a kernel that's separable in x&y.
- Par 2 should start by saying the intention is to uniquely identify peaks. The last sentence is missing some words.

Sec 4.4.2:

- Should be stated here and in the Fig 1 caption if these aren't straight line paths. Also, which path is chosen in the event that there are several?

Sec 4.4.3:

- "sigma_PSF which different" -> "sigma_PSF, which is different"
- "and a trend this the" -- fix wording
- semi-colon should be period before "The sums"
- "be a large amount" -> "by a large amount"

Sec 4.5.1:

- PSF variations are due to optical aberration (and defocus), not-flatness of the CCDs, and atmospheric variation. It would be good to tell the reader the typical scale and amplitude of variations due to each of these. This may even warrant inclusion of an image of the PSF width variations for a typical exposure.
- Please state whether the PSF model is this set of formulae evaluated at the pixel centers, or must be integrated over the pixel, and the reason for the choice.
- There are a few uses of "interpolation" in this section, the first use is presumably "linear interpolation", but the details of this for PSF interpolation are worth describing.
- The last paragraph and formula in this section is inscrutable as $R, R_0, R_X, \dots$ are undefined.

Sec 4.5.2:

- Since the GAIA catalog is now available, an interesting question is whether using that catalog for PSF star selection would be preferable to the heuristic of selecting such stars from the PS1 data. An interesting metric would be the fraction of PS1 PSF stars are confirmed to be point sources by GAIA.

Sec 4.5.3:

- Please present the number of grid cells in these fits also in terms of the physical scale (in arcsec) on the sky for those grids. Both in the text and Table 5. This can be tied back to the requested description of the expected PSF variations in Sec 4.5.1.
- As discussed at the start of this report, the handling of masked pixels should be described here. Some measurements (such as aperture flux) are formally undefined with even a single masked pixel; are those reported as undefined measurements, or are they measured with the pixels first replaced based upon interpolation or linear prediction or some other method?

Sec 4.5.3:

- "smf/cmf files" are not defined or referenced anywhere else in this paper. PSPS if referred to few enough instances (3) in the paper, that it could be explicitly defined in each of those instances. The term "public" here isn't what many people would expect, so should be defined as public to the other code.

Sec 4.6.4:

- "times" -> "\times"
- Not clear why the geometric mean trick is necessary in this calculation to reduce blending issues if neighboring sources have already been subtracted.

Sec 4.5.4:

- The term "size class" is only used once here, so perhaps only use the term "classification".

Sec 4.6.5:

- PSPHOT.EXT.NSIGMA.LIMIT is the only variable that looks like this in the paper, and isn't defined in the tables.
- Explicitly state that the cosmic ray identification is based upon sources appearing more morphologically compact than the PSF.

Sec 4.6.6:

- This section should be greatly clarified. It sounds like the intention was to perform the same joint fit as described in Sec 4.6.1, and it's not clear why this was something different. The current text reads as if it's a single iteration of fitting one star at time, subtracting fits only to brighter neighboring stars. The paragraph beginning "Sources which are blended..." should be relegated to the end of the section, and presented as a future development effort.
- Remind the reader that the 4 independent parameters includes a local sky value.
- "remaining flux should be below 1σ significance" -> "remaining flux divided by the errors should be normally distributed about 1"

Sec 4.6.7:

- This double-star case would be a common and interesting case, and it is worth demonstrating the validity of this approach. No doubt simulations were run showing this approach works for some separation and flux ratio range.

Sec 4.7:

- Completeness and purity should be discussed here. Even if this is more fully described in another paper, a summary of those findings could be included here.

Sec 4.8:

- The pronouncement that the wings of the PSF do not change significantly or quickly should be backed up with a reference, if possible. I'm not aware of a thorough study of this (although there may be one), and the PS1 data may be the best data set to ask these questions.
- "ApResid" is only sort of defined implicitly.
- It's interesting that the choice of the PSF model is made based upon the fainter, not the brighter, stars.
- An interesting result is the fraction of images that use each of the PSF models, and whether that strongly depends upon the density of stars and/or filter, or to what extent a similar image requires a different PSF model owing to atmospheric variations. For example, in the following section 4.9, has the same PSF model class been automatically selected for all 18 images?

Sec 4.9:

- A very interesting quantitative result that could be shown here is the variation in bright star magnitudes using aperture photometry. This would be a measure of the site's atmospheric transparency variations. There are results for this presented in the conclusions of an earlier PS1

paper ("Photometric Calibration..."), but those ~10 mmag numbers may be dominated by the PSF mis-estimation of bright stars rather than the atmospheric transparency variations.

Sec 5:

- "to all object" -> "to all objects"
- The definition of where in Galactic coordinates extended source photometry is performed is a little confusing. If the "l" in the in-text formula is galactic latitude, is it really the case that no extended source photometry is performed within 65 deg of the galactic center? Is this decision made for all sources within the same image, or is the decision made object-by-object?

Sec 5.2:

- The argument is that the surface brightness *profile shape* is conserved, not that the surface brightness is conserved with distance, which of course it is not.
- It may be useful to point out that these choices of Petrosian parameters to evaluate (R50 and R90 using circular apertures) appears to be the same as those in the SDSS catalogs. Can one expect those quantities to compare well to those in the PS1 catalog?

Sec 5.3:

- Eqn 28 is a blank line
- Eqn 27 would conventionally be written after eqns 29-32 as "with the definition $f_p = \dots$ " (remove the word "simplify").
- "and/or" -> "or" ?
- "In the analysis, convolved galaxy fit..." -> "In the convolved galaxy fits..."
- Graham & Driver missing in the References
- For the approximation of the central pixel values, the maximum fractional error of this approximation should be stated.

Sec 5.4:

- It's not clear what happens with poor-quality (worse than 1.5 or 2.0 arcsec seeing) images. Have they been included in the image stack, and the assumption made that the stacked seeing is always better than that?
- It's convenient that the aperture fluxes are made with the same choice of radii as used in SDSS. However, it should be noted here that the SDSS aperture fluxes in the SDSS catalogs are computed without any convolution. Since the median SDSS seeing is ~1.5 arcsec, those may be expected to compare well with the 1.5-arcsec convolved PS1 aperture fluxes.

Sec 5.5:

- State the seeing of these simulated images.

Sec 6 and 6.1:

- These sections could be clarified by splitting the sections, and calling the section something like "Averaged Single-Epoch Measurements" (where single-epoch could be "warp image" or whatever appropriate). Forced photometry is only performed on the stars, and it's something very different from the galaxies. The lensing subsection isn't "photometry" at all. What all 3 subsections have in common is that measurements are made on all of the single-epoch images, and then those measurements are averaged.
- The general description of the section should end with "variant of psphot", with the motivation being written such that it applies to both the averaged forced photometry on stars and the averaged single-epoch fits for galaxies

Sec 6.1 (now 6.2):

- CFHT, COSMOS should have citations to the relevant publications discussing their stacked images. There are multiple possible references for the mathematical appropriateness of image stacking, a nice recent discussion would be Zackay & Ofek 2016.
- The terms "skycell" and "warp image" are first used here without

definition. Are warp images the same as CAMERA and CHIP?

- For the forced photometry on single epoch images, is this a joint fit for overlapping objects?

Are overlapping galaxy models subtracted first? "The PSF model is fitted..." -> "The amplitude of the PSF model is fitted as the flux..."

Sec 6.2 (now 6.3):

- The reader only learns in the last few sentences that lensing parameters are an average of all of the single-epoch measurements. This should be stated upfront, and then again at the end of the subsection clarifying how the PSF systematics are removed. Phrases like "interpolated PSF ellipticities" are confusing, when I *think* what's being used are "interpolated star ellipticities".
- Was this lensing code used in any of the GREAT challenge papers, and if not, which code would it be most similar to?
- Define "KSB" and "HFK" references in-line
- "ie,," -> "ie,"
- "absoluate" -> "absolute"

Sec 7:

- This section is more cursory than the other sections. It's not clear how the end user should identify high-confidence asteroid or comet detections, and the completeness and purity of such detections. If these questions are covered in other Pan-STARRS papers, please reference them here.
- A basic piece of information that should be given is whether the differencing is performed on pairs of images, or single (warp) images compared to image stacks.
- "model from is" -> "model is"

Conclusions:

- The PS2 telescope is only mentioned here. At least give a reference.

Tables:

- For all of the tables, a caption should be included that explicitly describes all of the columns. Some readers will be using these papers as reference material, in which case the tables should be self-explanatory.

Tables 2,3,4:

- Please provide the names of these masks in the data products. From the text, the only mapping I could figure out is that Table 3 corresponds to "mask2".

Figures:

- For all the multi-panel figures, typical style would be to label each of the sub-panels (a), (b), etc, and describe in the caption.

Figure 2:

- "window" in the figure text should be " σ_w " to be consistent with the caption and text.
- For Figures 2,5,6, please do the mathematical calisthenics of stating how these instrumental magnitudes can be read as magnitudes above the detection threshold. If possible, it would be preferable to convert these figures to threshold magnitudes as done for Figure 7.

Figure 3:

- This figure isn't referenced in the text.
- State if each point is a single pixel value.
- State whether the black line model is part of the PSF models for these particular stars

Figure 4:

- State that this is for one image (or image stack?), with each source denoted by a point.

Figures 5 and 6:

- I can't find a definition of "STS" anywhere in the text.
- Upper panels should be labeled "Number of stars".

Figure 7:

- Caption should specify the seeing of these images (not in the text either).

Figures 8 and 9:

- These figures need much more explanation. The upper-left panel is presumably an RMS of the total magnitudes from the simulations? The upper right panel shows "ellipticity", which is not a defined quantity in the text. The other 4 panels could refer to the explanation in Sec 5.5.

References:

- It would be helpful to append "[Paper I]", "[Paper II]", etc, to the references for this sequence of papers.
- It would be helpful to append "[KSB]" and "[HFK]" to those references since they are cited that way in the text.
- Some additional references should be included; some suggestions above.