Draft October 8, 2015

Comparison between SHERA and SBProfile

ABSTRACT

This document describes the results of tests of SHERA and SBProfile to ensure that (a) they give consistent results for realistic galaxies and PSFs and (b) they are applying the shears sufficiently accurately for the purposes of the GREAT3 challenge.

1. Motivation

The SHERA software was designed specifically to simulate ground-based data using realistic training data from HST, and was written in IDL. Recently SBProfile, which was designed as a more general-purpose image simulator, was extended to include SHERA-like functionality using the SBInterpolatedImage class to represent general, non-parametric galaxy and PSF images. We want to ensure that the two codes give consistent results, and that the shears are applied to sufficiently high accuracy for use in GalSim and GREAT3.

A crucial step where differences can be introduced is interpolation. There are several steps where interpolation is needed: interpolation between pixels in real space, and in Fourier space for the shearing. These two interpolations need not be done in the same way; SBProfile allows different interpolation kernels for real- and Fourier-space operations.

1.1. The approaches

There are a few differences between the approaches in SHERA and in SBProfile when mapping a COSMOS galaxy to a sheared one at lower resolution.

- The main difference is that SBProfile supports any ratio of output to input pixel scale, which requires it to interpolate the target PSF in Fourier space. In contrast, SHERA has more restrictive rules about the ratio of output to input pixel scale (requiring that $5\times$ (output pixel scale)/(input pixel scale) be an integer), but this requirement allows the code to avoid explicitly interpolating the target PSF in real space. Instead, it is implicitly interpolated, via padding in Fourier space, which is equivalent to the ideal sinc interpolation in real space. Clearly, we require the more general SBProfile treatment for GalSim, and it will be interesting to compare these different approaches to the interpolation of the PSFs.

- SBProfile allows (and requires) a choice of interpolation kernel in real space. All Fourier operations in SBProfile account for the fact that the real-space image will be interpolated and should *not* be wrapped.

- For the interpolation that is used for the Fourier-space shearing step, SHERA uses a specific interpolation kernel, cubic interpolation (a windowed appoximation to a sinc based on cubic polynomials, using 16 points for a 2d image). SBProfile defaults to a quintic polynomial 6×6 pixel interpolant, but allows the choice of other interpolation kernels. See the document by Bernstein & Gruen (2012) for detailed discussion of the impact of interpolation errors and padding on the accuracy of shearing and resampling via DFTs.

- SBProfile will zero-pad images to square linear dimensions 2^n or 3×2^n for efficient FFTs. SHERA has rather more arcane rules that require the galaxy image and the target PSF to be related by a factor of output vs. input pixel scale (to avoid having to interpolate the target PSF at all).

- SHERA suffers from some annoying centroiding issues due to the use of IDL convolution routines.

- SHERA and SBProfile have different flux normalization conventions due to their different purposes. In particular, SBProfile seeks to preserve the surface brightness whereas SHERA asks the user to specify a target flux normalization.

- SHERA is carrying out a pseudo-deconvolution whereas SBProfile is carrying out a full deconvolution. This should not matter as long as the pseudo-deconvolution properly looks like a deconvolution for all k that are not killed off by the target PSF.

- The final resampling (via interpolation or subsampling) takes place in Fourier domain for SBProfile, in real space for SHERA.

1.2. Issues

Comparison of results between the two codes is complicated by the different conventions for centroiding and flux normalization, and by the different rules for array sizes. For our initial tests, to allow for compatible input image sizes between the codes, we require output vs. input pixel size $= 2^n$. We chose $n = 3$, so the ground-based telescope for which we carry out the tests has 0.24 arcsec pixels. (Note that we still use SDSS PSFs when we need real ones. We are simply lying to the code about the pixel size for those PSFs, for our own convenience.) Also, since output vs. input pixel sizes are an integer, the final resampling to the target pixel size is simply a resampling process. We will eventually want to test the effects of resampling via interpolation, but that test can take place at a later stage.

2. The PSF test and non-sheared galaxy tests

We begin with a test for which we know the answer: we choose some typical COSMOS PSF as our "galaxy," so that when we carry out PSF-matching, the final "galaxy" image should equal the target PSF. This test does not involve shearing, it only tests PSF-matching for rather arbitrary images. We also carry out the PSF-matching for three sample galaxies, where the true answer is not known.

For this test, we compare three types of outputs: we compare the final image on the target pixel scale; and we compare it on the original pixel scale (after PSF-matching, which includes the target pixel response function). Since the ratio of pixel scales is an integer, the first image comes from strict subsampling of the second image.

As an aside, we also compare a real-space version of the target PSF interpolated to the original COSMOS pixel scale, as a test of our interpolators. This test suggests that our cubic convolution implementations do essentially the same thing: the moments of the interpolated PSFs agree at the 10^{-5} level.

In the initial version of the 1st and 2nd tests (final simulated image on target and initial pixel scales), we found that the first test gave results that agree down to the 3×10^{-4} level for the sum of $M_{xx} + M_{yy}$, and 3×10^{-6} in ellipticity – but the second test gave differences of order a few percent, with SBProfile outputs being larger and rounder than the SHERA outputs.

Gary's theory is that this relates to the fact that his Fourier-domain treatment includes operations to represent the interpolation of the target PSF. The cubic interpolation effectively broadens the PSF slightly, so SBProfile gives broader outputs at the initial pixel scale, but not at the final pixel scale (where the resampling essentially means there is no interpolation). To test the theory that this difference comes from the SBProfile inclusion of the cubic interpolant as part of the definition of the PSF, Gary replaced the cubic interpolation of the target PSF with an $N = 7$ Lanczos filter. This filter should more closely approximate what SHERA does, i.e. no interpolation of the target PSF, but rather padding and embedding it into some larger array, which is equivalent to sinc interpolation. When he does this, the $M_{xx} + M_{yy}$ from SHERA and SBProfile at the initial COSMOS pixel scale agree to a few $\times 10^{-4}$, and the ellipticities agree to the fifth decimal place.

Conclusion for GalSim: we need to keep in mind that interpolation of the target PSF (either implicitly via FTing and padding, or explicitly in real or Fourier space) can amount to a different definition of the PSF, and we must decide what definition to use. Ultimately it comes down to assumptions about what astronomical objects look like between the samples that make up the pixelated images.

3. Shear

We have to test the accuracy of applied shears. There is no serious reason to expect the methods to disagree with each other (given that we established that they carry out cubic interpolation nearly identically), but this test is still important, particularly a test of absolute rather than relative accuracy.

3.1. Accuracy with respect to known analytic model

We have carried out tests using Gaussians, again adopting the initial and final pixel scales of $0.03''$ and $0.24''$ so we do not have to worry about differences due to how resampling is carried out. Our Gaussian PSFs have FWHM of 3.5 pixels, and the Gaussian galaxy has a FWHM twice that of the final target PSF. We considered shears of $(0, 0)$, $(0.02, 0.)$ and $(0., 0.05)$, and checked our simulated ground-based images (sheared and convolved with target PSF) versus our expectations for what the moment matrix should look like.

For the unsheared case, SBProfile gives a final simulated images with moments M_{xx} and M_{yy} that agree with the ideal case at the -0.06% and -0.03% level for Lanczos 5th and 9th order real-space interpolation kernels, respectively (used when interpolating the target PSF). The agreement was worse when using the cubic interpolation kernel, as seen in tests in previous sections. SHERA gives moments M_{xx} and M_{yy} that agree with the ideal case to better than the 10^{-6} level, due to the fact that the PSF is effectively interpolated with a sinc.

For the sheared case, SBProfile gives ellipticities that are accurate to 5 parts in 10^4 for Lanczos-5, 2 parts in 10^4 for Lanczos-9. SHERA results initially suggested some substantial error, but it turns out that this came from the relatively small postage stamp sizes used here (which is different from an actual use case for SHERA, since the COSMOS postage stamps that are provided have large amounts of padding). When the postage stamp sizes were increased to provide a level of padding comparable to the real training data, the errors in the final ellipticity were ~ 2 parts in 10^4.

3.2. Relative accuracy

Real galaxies, SBProfile vs. SHERA: in progress. The value in this comparison compared to the previous is that shearing realistic galaxy profiles might be harder than shearing nice simple Gaussians.

4. Resampling

Once we understand the results of the above tests, we may want to do some tests that require resampling to non-integer ratio pixel scales, though I think we do have a basic understanding of what is going on here.

5. Outstanding issues and conclusions

As we found in the first test, we need to be sure to understand the impact of resampling with a given interpolant in Fourier space (which gives errors periodic in k, and real-space ghosts) or real space (which gives errors periodic in x, and Fourier-space ghosts), and the impact on the effective PSF. At some level, this will come down to arbitrary decisions about what the objects we are observing look like between/beyond the resampled pixel grid. An important point to keep in mind, for perspective, is that there are systematic limitations in the training data that may be more important than the low-level differences we see here. The main (but not only) such limitations include (1) the fact that we use MultiDrizzle outputs, which include some aliasing (see work by Fruchter 2011, or Rowe, Hirata, & Rhodes 2011 on this topic; it arises because the undersampled individual exposures must be interpolated), and (2) the use of Tiny Tim PSFs, which do not perfectly represent the real ACS PSFs. For GREAT3, we are likely to circumvent (2) by carrying out a PCA modeling of real stars in the ACS images, but we will almost certainly not do anything about (1).

The critical issue for GalSim is not so much that the galaxies look exactly like the real galaxies on the sky (as long as they do not look so different that size- and profile-dependent biases are significantly affected). Rather, GalSim must draw sheared galaxies that are very precisely equivalent to sheared versions of the un-sheared galaxies that it draws. In this respect our goal is that the shear inferred from GalSim images be accurate to well below 1 part in 10^3. Since the choice of real-space interpolant only affects the former, not the latter issue, any consistent choice should be sufficient. Tests so far indicate that SBProfile and SHERA agree and are both correct on shear at the required level, as long as sufficient zero-padding is done before the FFTs.

A point that Gary raised to consider for the future: are our images giving surface brightness (the assumption of SBProfile) or flux per pixel (the assumption of SHERA, which means to match to some known object flux in ground-based data)? And when we add magnification to the pixel, do we want to conserve flux or surface brightness? (SBProfile does the latter. We should make this choice clear and decide whether it makes sense for us for GalSim. I think it does.)

6. Conclusions and decisions to be made

The above comparison suggests that provided we choose carefully what interpolants to use, SBProfile should allow us to simulate sheared, realistic galaxies at the level of precision we need.

There are several places where interpolation must occur, and it's not clear that the same level of accuracy is needed for each. In summary, these places are:

- Interpolation of the target PSF to get a higher resolution version.
- Shearing.
- Resampling.

For interpolation of the target PSF, we can see the effects in the tests above with Gaussians. 5th order Lanczos gives moments that are accurate to 5×10^{-4}, or linear sizes that are accurate to $\sim 2 \times 10^{-4}$. Given the aforementioned uncertainties in the training data (due to MultiDrizzle, Tiny Tim) I think it does not make sense to optimize for even greater accuracy than that in the sizes. It is arguable whether even this is necessary, and we can consider less accurate interpolations such as quintic for this stage (though we already know that cubic interpolants give differences of order a few %, which seems dicey).

For shearing, where we would like our shears to be accurate at the 10^{-4} level, it seems that we might require 9th order Lanczos in SBProfile. There might be a little room to change the order (should be > 5), but certainly cubic/quintic interpolation kernels are inadequate.

For resampling, is further testing required? The conclusions are likely the same as for the interpolation of the target PSF (rather than the more stringent requirements for shearing).