Tractor Documentation

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Contents

CHAPTER 1

Introduction to using The Tractor

The Tractor is a code for optimizing or sampling from *models* of astronomical objects. The approach is *generative*: given astronomical sources and a description of the image properties, the code produces pixel-space estimates or predictions of what will be observed in the images. We use this estimate to produce a likelihood for the observed data given the model: assuming our model space actually includes the truth (it doesn't, in detail), then if we had the optimal model parameters, the predicted image would only differ from the actually observed image by noise. Given a noise model of the instrument and assuming pixelwise independent noise, the log-likelihood is just the negative chi-squared difference: (image - model) / noise.

To actually use the Tractor code to infer the properties of astronomical objects in your images, you will probably have to write a *driver* script, which will read in your data of interest, create *tractor.Image* objects describing your images, and source objects describing the astronomical sources of interest. The Tractor does not (at present) create sources itself; you have to initialize it with reasonable guesses about the objects in your images.

***tractor.Image* objects carry the data, per-pixel noise sigma (we** usually work with inverse-variance), and a number of *calibration* parameters. These include the PSF model, astrometric calibration (WCS), photometric calibration, and sky background model. Each of these calibrations can be parameterized and its parameters fit alongside the properties of the astronomical sources.

1.1 Sources, positions, and brightnesses

***tractor.Source* objects are rather nebulously defined, as we will see** below. A simple example is the *tractor.PointSource* class, which has a "position" and a "brightness". A *Source* object must be able to *render* its appearance in a given *tractor.Image*; that is, is must be able to produce a pixel-space model of what it would look like in the given image. To do this, it must use the image's calibration objects to convert the source's representation of its position into pixel space (via the image's WCS), convert its representation of its brightness into pixel counts (via the image's photometric calibration or "photoCal"). It also needs the image's PSF model.

The core Tractor code does not know or care about the exact types (python classes) you use to represent the position and brightness. The only requirement for a "position" or "brightness" class is that it have the right "duck type", and that the image's PhotoCal or WCS objects can convert it to image space. That is, the class you use for the "position" of sources must match the class you use for the "WCS" of the images, and the "brightness" of the sources must match the "PhotoCal" of the images. Let's see an example to clarify this.

In this example, we are working in pixel space and raw counts; we use the *PixPos* class to represent pixel positions, and the *Flux* class to represent the image counts. We can then use the "null" calibration classes, which just pass through the position and flux values unmodified.

```
from tractor import *

source = PointSource(PixPos(17., 27.4), Flux(23.9))

photocal = NullPhotoCal()
wcs = NullWCS()

counts = photocal.brightnessToCounts(source.getBrightness())
x,y = wcs.positionToPixel(source.getPosition())
print 'source', source
print 'counts', counts, 'x,y', x,y
```

Which prints:

```
source PointSource at pixel (17.00, 27.40) with Flux: 23.9
counts 23.9 x,y 17.0 27.4
```

Instead, we could chose to work in RA,Dec coordinates, so we would use the *RaDecPos* class to represent the positions of sources in celestial coordinates, and one of the WCS calibration classes that expect celestial coordinates. Similarly, we could decide to work with brightness represented in *Mags*, and use a *MagsPhotoCal*.

```
from tractor import *
from astrometry.util.util import Tan

source = PointSource(RaDecPos(42.3, 9.7), Mags(r=12., i=11.3))

photocal = MagsPhotoCal('r', 22.5)
wcs = FitsWcs(Tan(42.0, 9.0, 100., 100., 0.1, 0., 0., 0.1, 200., 200.))

counts = photocal.brightnessToCounts(source.getBrightness())
x,y = wcs.positionToPixel(source.getPosition())

print 'source', source
print 'photocal', photocal
print 'wcs', wcs
print 'counts', counts, 'x,y', x,y
```

Which prints:

```
source PointSource at RaDecPos: RA, Dec = (42.30000, 9.70000) with Mags: i=11.3, r=12
photocal MagsPhotoCal(band=r, zp=22.500)
wcs FitsWcs: x0,y0 0.000,0.000, WCS TAN: crpix (100.0, 100.0), crval (42, 9), cd (0.1,
↪ 0, 0, 0.1), image 200 x 200
counts 15848.9319246 x,y 101.957357071 106.001652903
```

Notice a few things here: we created a *Mags* object with *r* and *i*-band mags. Then when we created the *photocal*, we told it that this image is *r* band. The Tractor doesn't care how many parameters you use to represent your brightness, all it cares is that your *PhotoCal* class can convert it to counts. You could imagine representing a star's brightness in terms of angular diameter and black-body temperature, and have your PhotoCal integrate its spectrum through a filter curve.

In this example, we gave the source magnitudes in two different bands. If we had, say, an image in each band, we count then fit its position and flux in both bands. The position (in RA,Dec) would be fit to jointly optimize the likelihood in the two images, while the fluxes would be fit independently of each other. The *r*-band image would just have nothing

to say about the *i*-band magnitude, and vice versa.

In the Tractor code, the "duck types" are defined in the file *tractor/ducks.py*. This code is not actually used, it is just documentation written in code. A toolbox of typical choices for position and brightness and their corresponding WCS and PhotoCal are given in the file *tractor/basics.py*.

1.2 Parameters

Before going any further, let's look at some of the infrastructure for how the Tractor deals with parameters. In the Tractor code, most objects (sources, image calibration objects) must be *Params* duck-type objects. That is, a source should act like a *Params* object, as should a *PhotoCal* object. The most important function calls are shown here:

```
>>> from tractor import *
>>> pos = RaDecPos(42.3, 9.7)
>>> print pos
RaDecPos: RA, Dec = (42.30000, 9.70000)
>>> print pos.getParams()
[42.3, 9.7]
>>> print pos.getParamNames()
['ra', 'dec']
>>> print pos.getStepSizes()
[0.00010145038861680802, 0.0001]
>>> pos.setParams([42.7, 9.3])
>>> print pos
RaDecPos: RA, Dec = (42.70000, 9.30000)
>>> pos.setParam(1, 10.0)
>>> print pos
RaDecPos: RA, Dec = (42.70000, 10.00000)
```

Most of the Tractor's infrastructure for dealing with params is in the *tractor/utils.py* file, which is not easy reading. The hope, however, is that the resulting API is flexible and easy to use.

We often want to "compose" objects out of sub-objects (a *PointSource* has a position and a brightness), so there is a class for that, called *MultiParams*. It is also nice to be able to parameters or sub-objects by name; this is accomplished by the *NamedParams* mix-in class, though you'll probably never have to use that in your own code. For example:

```
>>> from tractor import *
>>> source = PointSource(RaDecPos(42.3, 9.7), Mags(r=99.9))
>>> print source
PointSource at RaDecPos: RA, Dec = (42.30000, 9.70000) with Mags: r=99.9
>>> print source.pos
RaDecPos: RA, Dec = (42.30000, 9.70000)
>>> print source.brightness
Mags: r=99.9
>>> print source.pos.ra
42.3
>>> print source.brightness.r
99.9
>>> print source.getParams()
[42.3, 9.7, 99.9]
>>> print zip(source.getParamNames(), source.getParams())
[('pos.ra', 42.3), ('pos.dec', 9.7), ('brightness.r', 99.9)]
```

Notice that *source.getParams()* just concatenates the *getParams()* results from its *pos* and *brightness* sub-objects. This is a really general theme in the Tractor. A Tractor *Image* object is composed of all its calibration sub-objects; *Image.getParams()* gives a full description of the calibration parameters of the image. Similarly, a Tractor *Catalog* is a

list-like container of sources whose *getParams()* method just concatenates the *getParams()* of all the source it contains. Taking this one step further, a *Tractor* object itself is composed of *Images* and a *Catalog*.

1.3 Thawing/Freezing Params

A powerful feature of the Tractor is that you can "freeze" a subset of the parameters – hold them fixed and exclude them from fitting. This power comes at a price, though (doesn't it always?); freezing the right parameters can be a bit tricky, and objects with frozen parameters might not always act the way you expect.

For *MultiParams* objects, you can freeze and thaw sub-objects by name. A parameter is considered "thawed" if the full path from the Tractor object to the parameter is thawed.

One possibly surprising thing about frozen parameters is that they **disappear** from the *getParams()* and *getParamNames()* lists; they are also not counted in *numberOfParams()*, and *setParams()* will skip past them. Frozen parameters effectively disappear from view:

```
>>> from tractor import *
>>> cat = Catalog(PointSource(RaDecPos(42.3, 9.7), Mags(r=99.9)))
>>> print cat
Catalog: 1 sources, 3 parameters
>>> print zip(cat.getParamNames(), cat.getParams())
[('source0.pos.ra', 42.3), ('source0.pos.dec', 9.7), ('source0.brightness.r', 99.9)]
>>> cat[0].freezeParam('pos')
>>> print zip(cat.getParamNames(), cat.getParams())
[('source0.brightness.r', 99.9)]
```

Here we froze the "pos" sub-object of the *PointSource*, so it disappears from view. We could thaw the position, but then freeze its RA component:

```
>>> cat[0].thawParam('pos')
>>> cat[0].pos.freezeParam('ra')
>>> print zip(cat.getParamNames(), cat.getParams())
[('source0.pos.dec', 9.7), ('source0.brightness.r', 99.9)]
```

Handy functions include:

```
>>> cat.thawAllRecursive()
>>> print zip(cat.getParamNames(), cat.getParams())
[('source0.pos.ra', 42.3), ('source0.pos.dec', 9.7), ('source0.brightness.r', 99.9)]
>>> cat.freezeAllRecursive()
>>> cat.thawPathsTo('r')
True
>>> print zip(cat.getParamNames(), cat.getParams())
[('source0.brightness.r', 99.9)]
>>> print 'Thawed(self)   Thawed(parent)   Param', '\n', '-'*50
>>> for param, tself, tparent in cat.getParamStateRecursive():
...     print '   %5s      %5s           ' % (tself, tparent), param
Thawed(self)   Thawed(parent)   Param
--------------------------------------------------
    True        True           source0
   False        True           source0.pos
   False       False           source0.pos.ra
   False       False           source0.pos.dec
    True        True           source0.brightness
    True        True           source0.brightness.r
```

The last table shows that the *freezeAllRecursive()* call froze both the source *pos* but also *pos.ra* and *pos.dec*; just thawing *pos* won't cause *ra* and *dec* to become active again; we have to thaw the full path down to *ra* and *dec*:

```
>>> cat[0].thawParam('pos')
>>> cat.printThawedParams()
source0.brightness.r = 99.9
>>> cat[0].pos.thawAllParams()
>>> cat.printThawedParams()
source0.pos.ra = 42.3
source0.pos.dec = 9.7
source0.brightness.r = 99.9
```

1.4 Optimization / Fitting

So far we haven't actually created a *Tractor* object or fit anything. Time to get down to business.

As an example, let's create a synthetic image manually, and then use the Tractor to fit a source model to it.

```
import numpy as np
import pylab as plt
from tractor import *

# Size of image, centroid and flux of source
W,H = 25,25
cx,cy = 12.8, 14.3
flux = 12.
# PSF size
psfsigma = 2.
# Per-pixel image noise
noisesigma = 0.01
# Create synthetic Gaussian star image
G = np.exp(((np.arange(W)-cx)[np.newaxis,:]**2 +
            (np.arange(H)-cy)[:,np.newaxis]**2)/(-2.*psfsigma**2))
trueimage = flux * G/G.sum()
image = trueimage + noisesigma * np.random.normal(size=trueimage.shape)

# Create Tractor Image
tim = Image(data=image, invvar=np.ones_like(image) / (noisesigma**2),
            psf=NCircularGaussianPSF([psfsigma], [1.]),
            wcs=NullWCS(), photocal=NullPhotoCal(),
            sky=ConstantSky(0.))

# Create Tractor source with approximate position and flux
src = PointSource(PixPos(W/2., H/2.), Flux(10.))

# Create Tractor object itself
tractor = Tractor([tim], [src])

# Render the model image
mod0 = tractor.getModelImage(0)
chi0 = tractor.getChiImage(0)

# Plots
ima = dict(interpolation='nearest', origin='lower', cmap='gray',
           vmin=-2*noisesigma, vmax=5*noisesigma)
imchi = dict(interpolation='nearest', origin='lower', cmap='gray',
```

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```
                vmin=-5, vmax=5)
plt.clf()
plt.subplot(2,2,1)
plt.imshow(trueimage, **ima)
plt.title('True image')
plt.subplot(2,2,2)
plt.imshow(image, **ima)
plt.title('Image')
plt.subplot(2,2,3)
plt.imshow(mod0, **ima)
plt.title('Tractor model')
plt.subplot(2,2,4)
plt.imshow(chi0, **imchi)
plt.title('Chi')
plt.savefig('1.png')

# Freeze all image calibration params -- just fit source params
tractor.freezeParam('images')

# Save derivatives for later plotting...
derivs = tractor.getDerivs()

# Take several linearized least squares steps
for i in range(10):
    dlnp,X,alpha = tractor.optimize()
    print 'dlnp', dlnp
    if dlnp < 1e-3:
        break

# Get the fit model and residual images for plotting
mod = tractor.getModelImage(0)
chi = tractor.getChiImage(0)
# Plots
plt.clf()
plt.subplot(2,2,1)
plt.imshow(trueimage, **ima)
plt.title('True image')
plt.subplot(2,2,2)
plt.imshow(image, **ima)
plt.title('Image')
plt.subplot(2,2,3)
plt.imshow(mod, **ima)
plt.title('Tractor model')
plt.subplot(2,2,4)
plt.imshow(chi, **imchi)
plt.title('Chi')
plt.savefig('2.png')

# Plot the derivatives we saved earlier
def showpatch(patch, ima):
    im = patch.patch
    h,w = im.shape
    ext = [patch.x0,patch.x0+w, patch.y0,patch.y0+h]
    plt.imshow(im, extent=ext, **ima)
    plt.title(patch.name)
imderiv = dict(interpolation='nearest', origin='lower', cmap='gray',
               vmin=-0.05, vmax=0.05)
```

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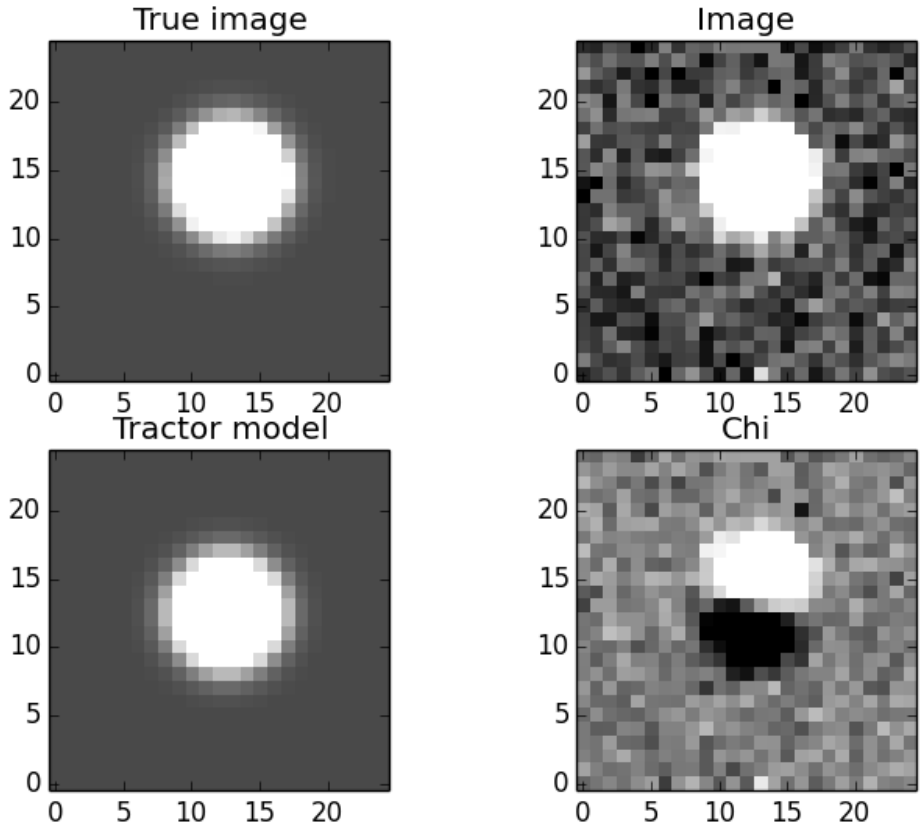
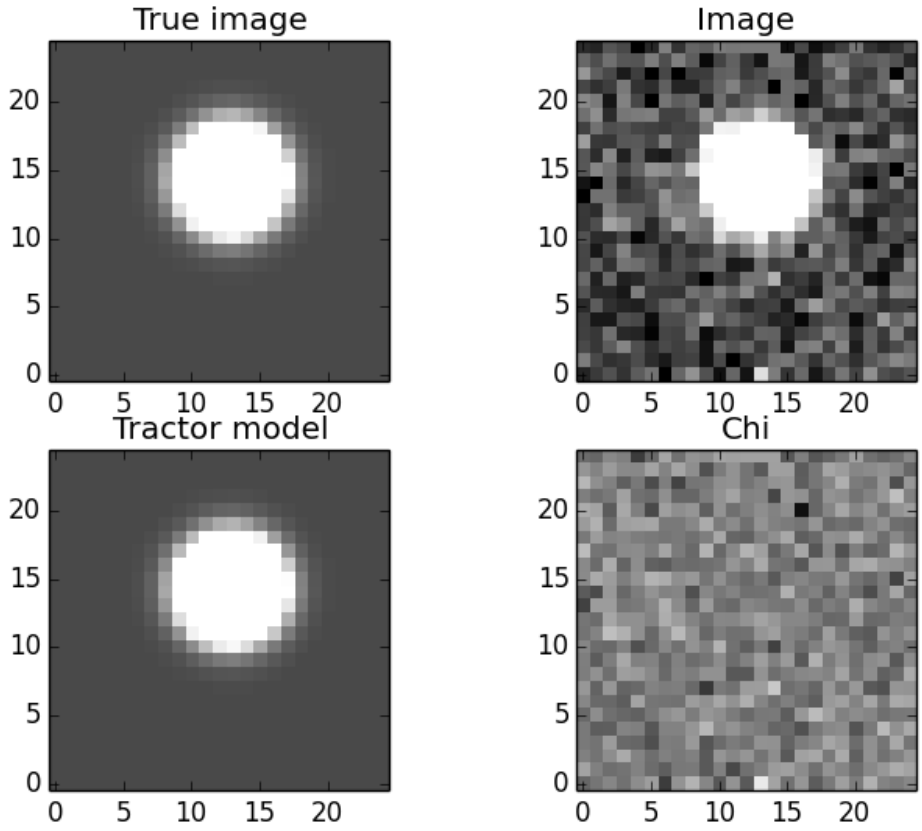
```
plt.clf()
plt.subplot(2,2,1)
plt.imshow(mod0, **ima)
ax = plt.axis()
plt.title('Initial Tractor model')
for i in range(3):
    plt.subplot(2,2,2+i)
    showpatch(derivs[i][0][0], imderiv)
    plt.axis(ax)
plt.savefig('3.png')
```

The plots look like:

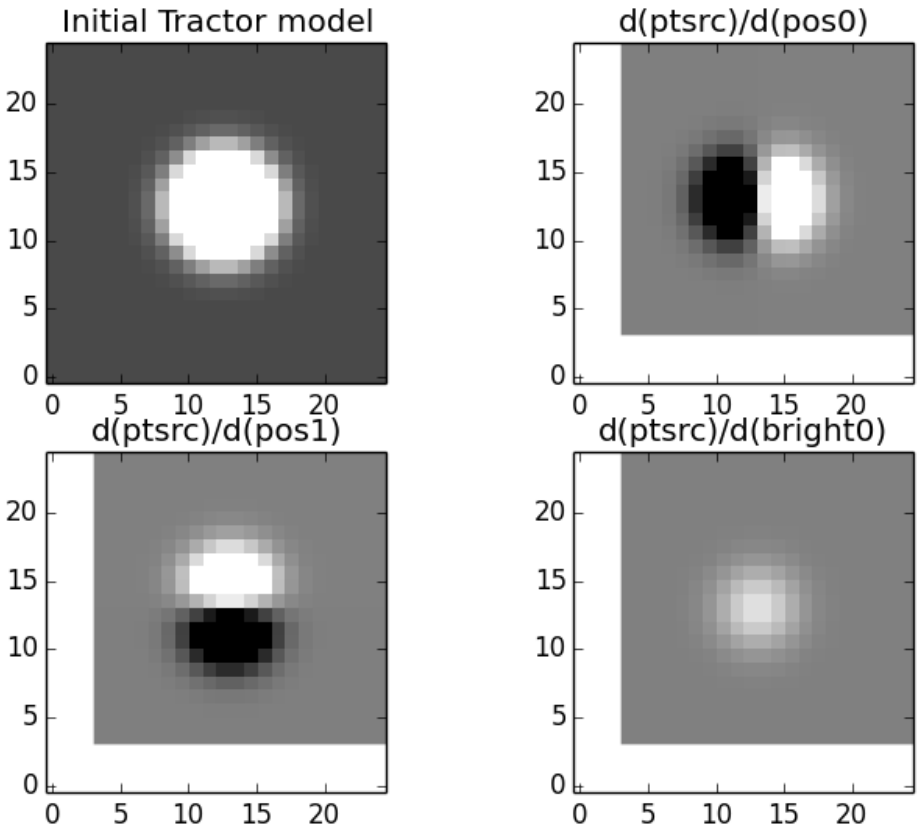
The “before” image—our initial Tractor model has the source a little too low and to the left, which you can see in the “chi” image.



The “after” image—the source position has been adjusted and the “chi” image looks like a noise field.



The "derivatives" image—the initial model, and its derivatives with respect to each of the parameters being fit. The fitter finds a linear combination of the derivatives that should minimize the residuals, then does line-search (since the minimum in the linearized problem may not coincide with the minimum in the real non-linear problem).



1.5 Multi-Image Optimization / Fitting

In the following example we will fit for the positions and fluxes of two point sources in two images with different point-spread functions and noise properties. The sources are within a few pixels of each other, so this is actually not a trivial problem for most source extraction routines, while for the Tractor the code is nearly identical to the easier single-image, single-source case.

```
import numpy as np
import pylab as plt
from tractor import *

def imshow(x, **kwa):
    plt.imshow(x, **kwa)
    plt.xticks([]); plt.yticks([])

# Size of image, centroids and fluxes of sources
W,H = 25,25
stars = [((12.8, 14.3), 12.), ((15.0, 11.0), 15.)]
# PSF sizes
psfsigmas = [2., 1.]
# Per-pixel image noise
noisesigmas = [0.01, 0.02]
```

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```
# Create synthetic Gaussian star images
trueimages = []
images = []
for psfsigma, noisesigma in zip(psfsigmas, noisesigmas):
    trueimage = np.zeros((H,W))
    for (cx,cy),flux in stars:
        G = np.exp(((np.arange(W)-cx)[np.newaxis,:]**2 +
                    (np.arange(H)-cy)[:,np.newaxis]**2)/(-2.*psfsigma**2))
        trueimage += flux * G/G.sum()
    image = trueimage + noisesigma * np.random.normal(size=trueimage.shape)
    trueimages.append(trueimage)
    images.append(image)

# Create Tractor Images
tims = [Image(data=image, invvar=np.ones_like(image) / (noisesigma**2),
              psf=NCircularGaussianPSF([psfsigma], [1.]),
              wcs=NullWCS(), photocal=NullPhotoCal(),
              sky=ConstantSky(0.))
              for image, noisesigma, psfsigma
              in zip(images, noisesigmas, psfsigmas)]

# Create Tractor sourcess with approximate position and flux
cat = [PointSource(PixPos(W/2.-1, H/2.-1), Flux(10.)),
       PointSource(PixPos(W/2.+1, H/2.+1), Flux(10.))]

# Create Tractor object itself
tractor = Tractor(tims, cat)

# Render the model images
mods0 = [tractor.getModelImage(i) for i in range(2)]
chis0 = [tractor.getChiImage(i)   for i in range(2)]

# Plots
ima = dict(interpolation='nearest', origin='lower', cmap='gray',
           vmin=-2*noisesigma, vmax=20*noisesigma)
imchi = dict(interpolation='nearest', origin='lower', cmap='gray',
             vmin=-5, vmax=5)
def plot_src_pos(srcs):
    ax = plt.axis()
    plt.plot([src.getPosition().x for src in srcs],
             [src.getPosition().y for src in srcs], 'r+')
    plt.axis(ax)
def plot_true_pos(stars):
    ax = plt.axis()
    plt.plot([cx for (cx,cy),flux in stars],
             [cy for (cx,cy),flux in stars], 'o', mec='r', mfc='none')
    plt.axis(ax)

plt.clf()
for i,(trueim,im,mod,chi) in enumerate(zip(trueimages,images,mods0,chis0)):
    plt.subplot(2,4, 4*i+1)
    imshow(trueim, **ima)
    plot_true_pos(stars)
    plt.title('True image')
    plt.subplot(2,4, 4*i+2)
    imshow(im, **ima)
    plot_true_pos(stars)
```

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```
    plt.title('Image')
    plt.subplot(2,4, 4*i+3)
    imshow(mod, **ima)
    plot_src_pos(cat)
    plt.title('Tractor model')
    plt.subplot(2,4, 4*i+4)
    imshow(chi, **imchi)
    plot_src_pos(cat)
    plt.title('Chi')
plt.savefig('4.png')

# Freeze all image calibration params -- just fit source params
tractor.freezeParam('images')

# Plot derivatives...
derivs = tractor.getDerivs()
def showpatch(patch, ima):
    im = patch.patch
    h,w = im.shape
    ext = [patch.x0-0.5,patch.x0+w-0.5, patch.y0-0.5,patch.y0+h-0.5]
    imshow(im, extent=ext, **ima)
    plt.title(patch.name.replace('d(ptsrc)', 'd'))
imderiv = dict(interpolation='nearest', origin='lower', cmap='gray',
               vmin=-0.05, vmax=0.05)
plt.clf()
for i,mod0 in enumerate(mods0):
    plt.subplot(4,4, 8*i+1)
    imshow(mod0, **ima)
    plot_src_pos(cat)
    ax = plt.axis()
    plt.title('Initial Tractor model')
    for j in range(6):
        plt.subplot(4,4, 8*i + (j/3)*4 + j%3 + 2)
        showpatch(derivs[j][i][0], imderiv)
        plt.axis(ax)
        plot_src_pos([cat[j/3]])
plt.savefig('5.png')

# Take several linearized least squares steps
for i in range(10):
    dlnp,X,alpha = tractor.optimize()
    print 'dlnp', dlnp
    if dlnp < 1e-3:
        break

# Get the fit model and residual images for plotting
mods = [tractor.getModelImage(i) for i in range(2)]
chis = [tractor.getChiImage(i)   for i in range(2)]
# Plots
plt.clf()
for i,(trueim,im,mod,chi) in enumerate(zip(trueimages,images,mods,chis)):
    plt.subplot(2,4, 4*i+1)
    imshow(trueim, **ima)
    plot_true_pos(stars)
    plt.title('True image')
    plt.subplot(2,4, 4*i+2)
    imshow(im, **ima)
```

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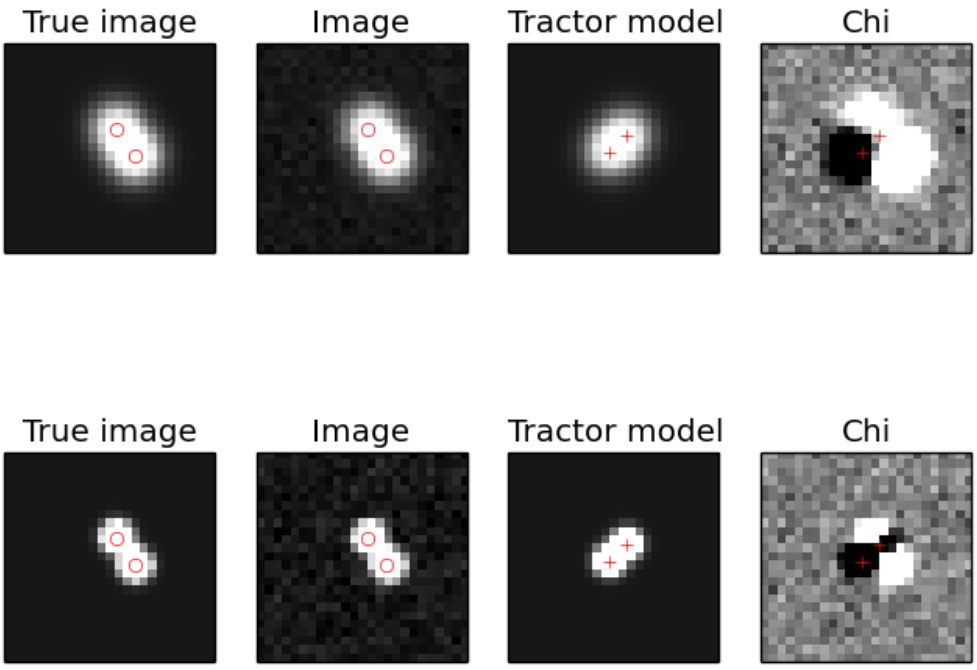
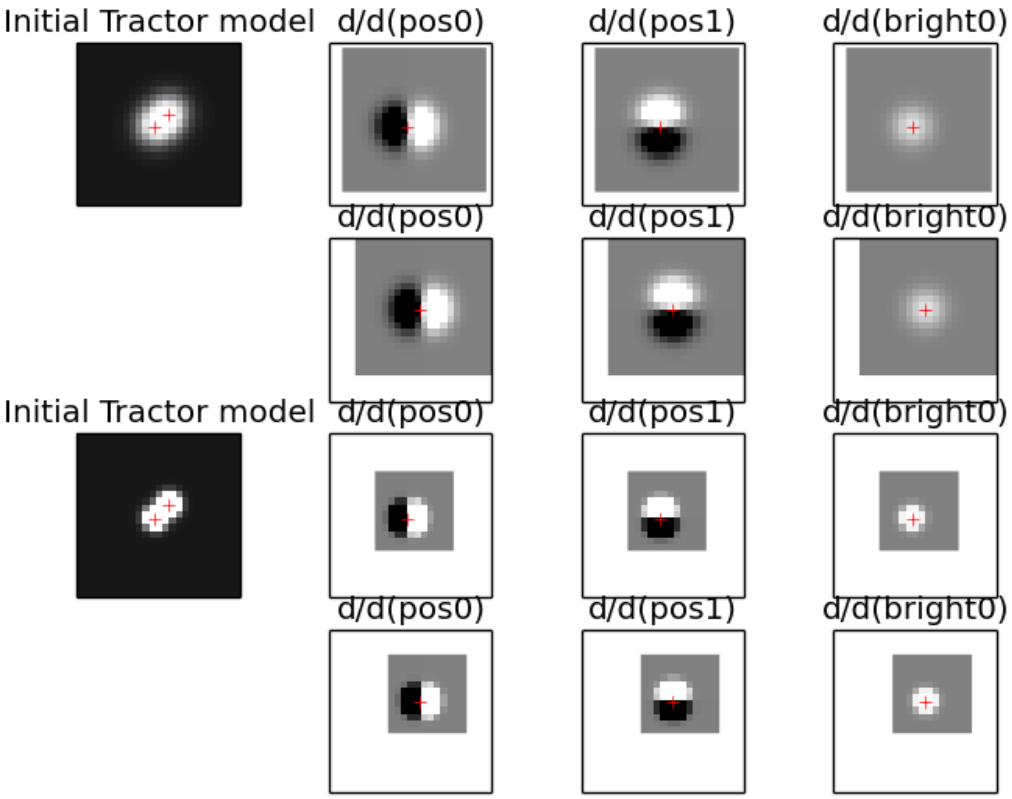
```
    plot_true_pos(stars)
    plt.title('Image')
    plt.subplot(2,4, 4*i+3)
    imshow(mod, **ima)
    plot_src_pos(cat)
    plot_true_pos(stars)
    plt.title('Tractor model')
    plt.subplot(2,4, 4*i+4)
    imshow(chi, **imchi)
    plot_src_pos(cat)
    plt.title('Chi')
plt.savefig('6.png')
```

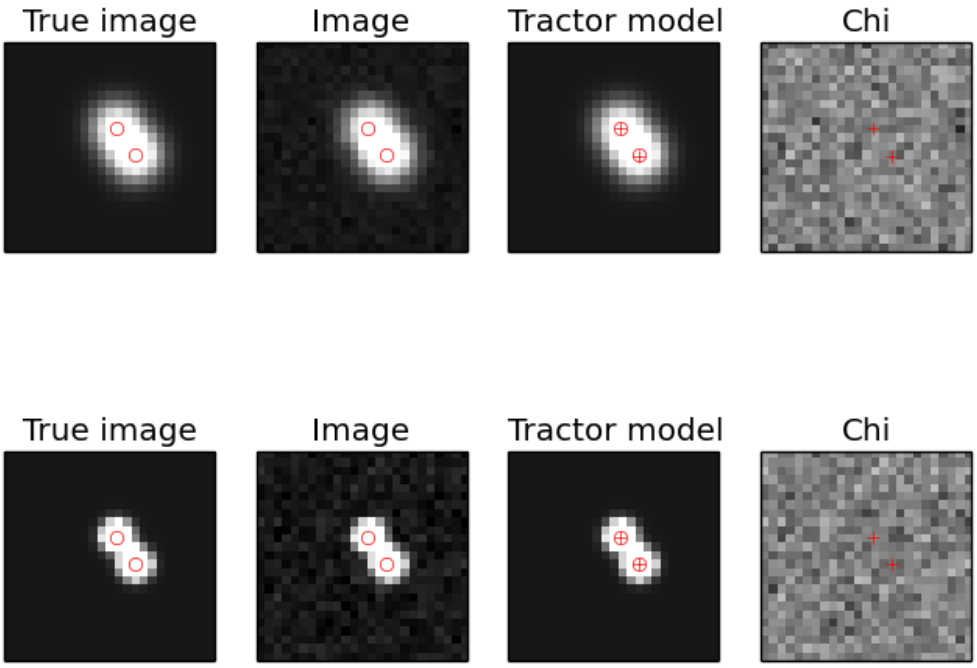
Here are the resulting images. First, the initial model. Note that we did not initialize the source positions very well.



Next, the derivatives.



Finally, the optimized model. The Tractor found the correct centroids and fluxes for the sources, leaving nothing but noise (by eye, at least).


True image
Image
Tractor model
Chi
True image
Image
Tractor model
Chi

CHAPTER 2

Introduction to using The Tractor (Part 2)

2.1 Galaxies

The Tractor currently supports parametric Exponential ("exp", *ExpGalaxy*) and deVaucoulers ("dev", *DevGalaxy*) galaxies, composite galaxies (deV+exp, *CompositeGalaxy* and *FixedCompositeGalaxy*), and general Sersic galaxies (*SersicGalaxy*). The dev and exp galaxies are in the *tractor.galaxy* package, while Sersic is in *tractor.sersic*.

Each of these galaxies is described by its position, brightness, and an ellipse describing its shape. Composite galaxies have a brightness and shape for the dev and exp components. FixedComposite has a single brightness and a *FracDev* parameter describing how the flux is split between the exp and dev components. Sersic galaxies also a Sersic index parameter.

A number of ellipse parameterizations are available, including *GalaxyShape* (radius, axis ratio, and position angle; in *galaxy.py*), *EllipseE* (radius, e1, e2)—which I believe are called g1,g2 in GalSim, and *EllipseESoft* (log-radius, ee1, ee2), where ee1,ee2 go through a sigmoid softening function (1-exp(-|eel)) to get to the standard e1,e2. This parameterization has the advantage that the parameter space is smooth and unbounded, which tends to make optimizers happy.

Let's see an example of creating some Galaxy objects.

```
import numpy as np
import pylab as plt
from tractor import *
from tractor.galaxy import *
from tractor.sersic import *

# size of image
W,H = 40,40

# PSF size
psfsigma = 1.

# per-pixel noise
noisesigma = 0.01
```

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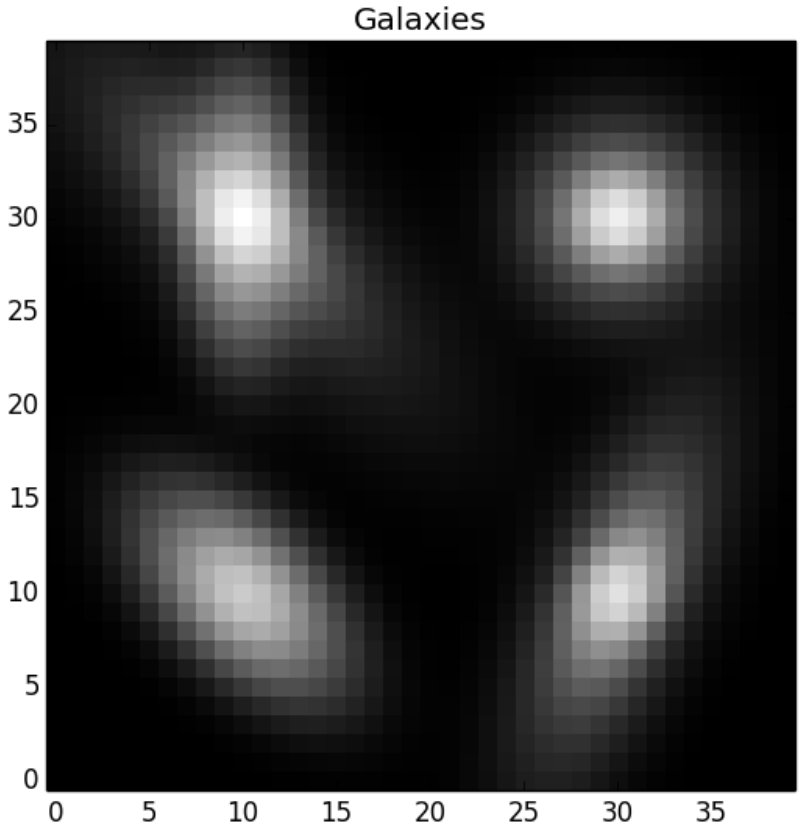
```
# create tractor.Image object for rendering synthetic galaxy
# images
tim = Image(data=np.zeros((H,W)), invvar=np.ones((H,W)) / (noisesigma**2),
            psf=NCircularGaussianPSF([psfsigma], [1.]))

sources = [ ExpGalaxy(PixPos(10,10), Flux(10.), GalaxyShape(3., 0.5, 45.)),
            CompositeGalaxy(PixPos(10,30),
                            Flux(10.), EllipseE(3., 0.5, 0.),
                            Flux(10.), EllipseE(3., 0., -0.5)),
            SersicGalaxy(PixPos(30,10), Flux(10.),
                         EllipseESoft(1., 0.5, 0.5), SersicIndex(3.)),
            FixedCompositeGalaxy(PixPos(30,30), Flux(10.), 0.8,
                                 EllipseE(2., 0., 0.),EllipseE(1., 0., 0.))]

tractor = Tractor([tim], sources)

mod = tractor.getModelImage(0)

# Plot
plt.clf()
plt.imshow(np.log(mod + noisesigma),
           interpolation='nearest', origin='lower', cmap='gray')
plt.title('Galaxies')
plt.savefig('7.png')
```

Notice that we can mix-and-match different ellipse types. The image looks like:


Galaxies
35
30
25
20
15
10
5
0
0
5
10
15
20
25
30
35

CHAPTER 3

Using the Tractor with GalSim images

In the example below, we will process images generated by a modified version of the GalSim *demo12.py* script (Original: https://github.com/GalSim-developers/GalSim/blob/master/examples/demo12.py ; Modified: https://github.com/dstndstn/tractor/blob/master/doc/galsim/demo12.py).

Using the Tractor with GalSim images requires creating a *tractor.Image* object and source (*PointSource*, *Galaxy*) objects describing the objects in your scene.

Let's start with the *Image*. For some experiments you would like to have the Tractor figure out the PSF itself, but here we will assume you want to tell it the true PSF model that was used. If you used a single Gaussian PSF in GalSim, that would look like:

```
from tractor import *
psf = NCircularGaussianPSF([sigma], [1.])
```

Be careful about PSF widths specified as full-width at half max (FWHM), or specified in arcseconds. All the Tractor PSF models describe the PSF sizes in *pixels*, and *standard deviations* (sigmas).

For WCS, if you are working with single images, or pixel-aligned multiple images, it will probably be easiest to work in pixel coordinates for positions. You will then use the *PixPos* class for your positions, and *NullWCS* (the default) for the WCS.

For photometric calibration ("photocal"), again it will probably be easiest to work directly in counts (*Flux* class) if you are doing single-band images, or *Fluxes* for multi-band. For *Flux*, you can keep the default *NullPhotoCal*, but for *Fluxes*, use *FluxesPhotoCal* or *LinearPhotoCal*, telling it the band name of the image you are processing:

```
from tractor import *

flux = Fluxes(r=100, g=40)
source = PointSource(PixPos(0.,0.), flux)

# If we're dealing with an r-band image:
photocal = FluxesPhotoCal('r')
```

The other thing you have to do is read the GalSim simulated pixels, and set up the inverse-variance ("invvar") map. Here I will assume the noise in the GalSim image is pixelwise independent Gaussian of known variance. I will assume

we are reading 3 epochs of simulated images, stored in a "data cube" format. The actual files used in this example can be found in the *tractor* git repository in the *doc/galsim* directory.

```
import numpy as np
import pylab as plt
import fitsio
from tractor import *
from tractor.galaxy import *

# These match the values in galsim/demo12.py
pixnoise = 0.02
psf_sigma = 1.5
bands = 'ugrizy'
nepochs = 3

# Read multiple epochs of imaging for each band.
mydir = os.path.dirname(__file__)
tims = []
for band in bands:
    fn = os.path.join(mydir, 'galsim', 'output', 'demo12b_%s.fits' % band)
    print 'Band', band, 'Reading', fn
    cube,hdr = fitsio.read(fn, header=True)
    print 'Read', cube.shape
    pixscale = hdr['GS_SCALE']
    print 'Pixel scale:', pixscale, 'arcsec/pix'
    nims,h,w = cube.shape
    assert(nims == nepochs)
    for i in range(nims):
        image = cube[i,:,:]
        tim = Image(data=image, invvar=np.ones_like(image) / pixnoise**2,
                    photocal=FluxesPhotoCal(band),
                    wcs=NullWCS(pixscale=pixscale),
                    psf=NCircularGaussianPSF([psf_sigma], [1.0]))
        tims.append(tim)

# We create a dev+exp galaxy with made-up initial parameters.
galaxy = CompositeGalaxy(PixPos(w/2, h/2),
                         Fluxes(**dict([(band, 10.) for band in bands])),
                         EllipseESoft(0., 0., 0.),
                         Fluxes(**dict([(band, 10.) for band in bands])),
                         EllipseESoft(0., 0., 0.))

tractor = Tractor(tims, [galaxy])

# Plot images
ima = dict(interpolation='nearest', origin='lower', cmap='gray',
           vmin=-5.*pixnoise, vmax=20.*pixnoise)
plt.subplots_adjust(left=0.05, right=0.95, bottom=0.05, top=0.92)
plt.clf()
for i,band in enumerate(bands):
    for e in range(nepochs):
        plt.subplot(nepochs, len(bands), e*len(bands) + i +1)
        plt.imshow(tims[nepochs*i + e].getImage(), **ima)
        plt.xticks([]); plt.yticks([])
        plt.title('%s #%i' % (band, e+1))
plt.suptitle('Images')
plt.savefig('8.png')
```

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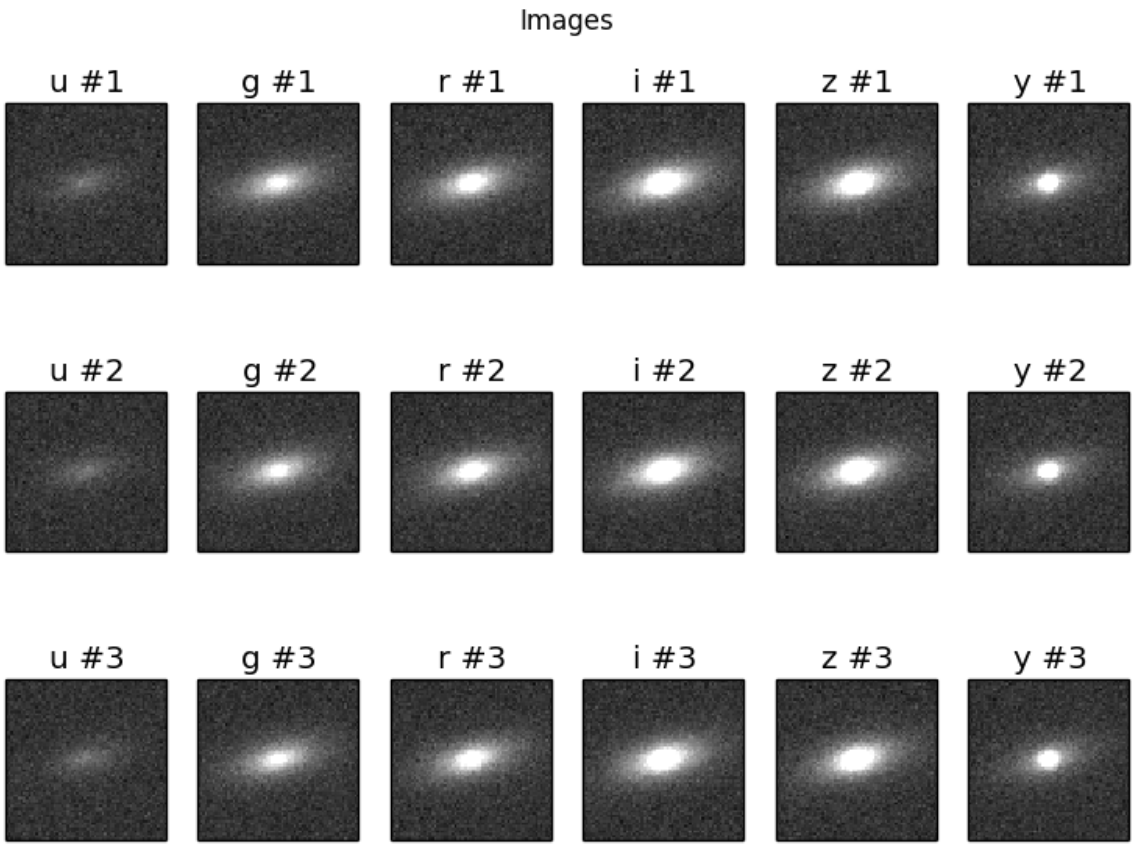
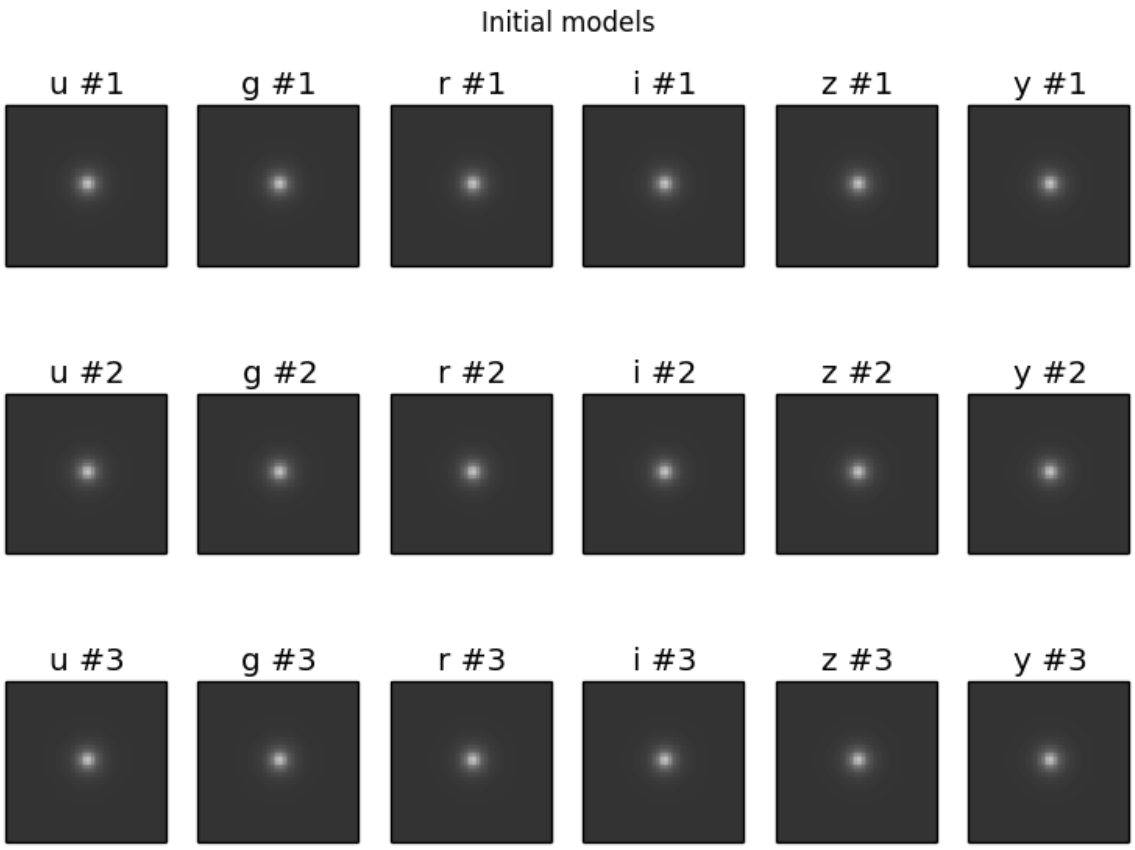
```
# Plot initial models:
mods = [tractor.getModelImage(i) for i in range(len(tims))]
plt.clf()
for i,band in enumerate(bands):
    for e in range(nepochs):
        plt.subplot(nepochs, len(bands), e*len(bands) + i +1)
        plt.imshow(mods[nepochs*i + e], **ima)
        plt.xticks([]); plt.yticks([])
        plt.title('%s #%i' % (band, e+1))
plt.suptitle('Initial models')
plt.savefig('9.png')

# Freeze all image calibration parameters
tractor.freezeParam('images')

# Take several linearized least squares steps
for i in range(20):
    dlnp,X,alpha = tractor.optimize()
    print 'dlnp', dlnp
    if dlnp < 1e-3:
        break

# Plot optimized models:
mods = [tractor.getModelImage(i) for i in range(len(tims))]
plt.clf()
for i,band in enumerate(bands):
    for e in range(nepochs):
        plt.subplot(nepochs, len(bands), e*len(bands) + i +1)
        plt.imshow(mods[nepochs*i + e], **ima)
        plt.xticks([]); plt.yticks([])
        plt.title('%s #%i' % (band, e+1))
plt.suptitle('Optimized models')
plt.savefig('10.png')

# Plot optimized models + noise:
plt.clf()
for i,band in enumerate(bands):
    for e in range(nepochs):
        plt.subplot(nepochs, len(bands), e*len(bands) + i +1)
        mod = mods[nepochs*i + e]
        plt.imshow(mod + pixnoise * np.random.normal(size=mod.shape), **ima)
        plt.xticks([]); plt.yticks([])
        plt.title('%s #%i' % (band, e+1))
plt.suptitle('Optimized models + noise')
plt.savefig('11.png')
```

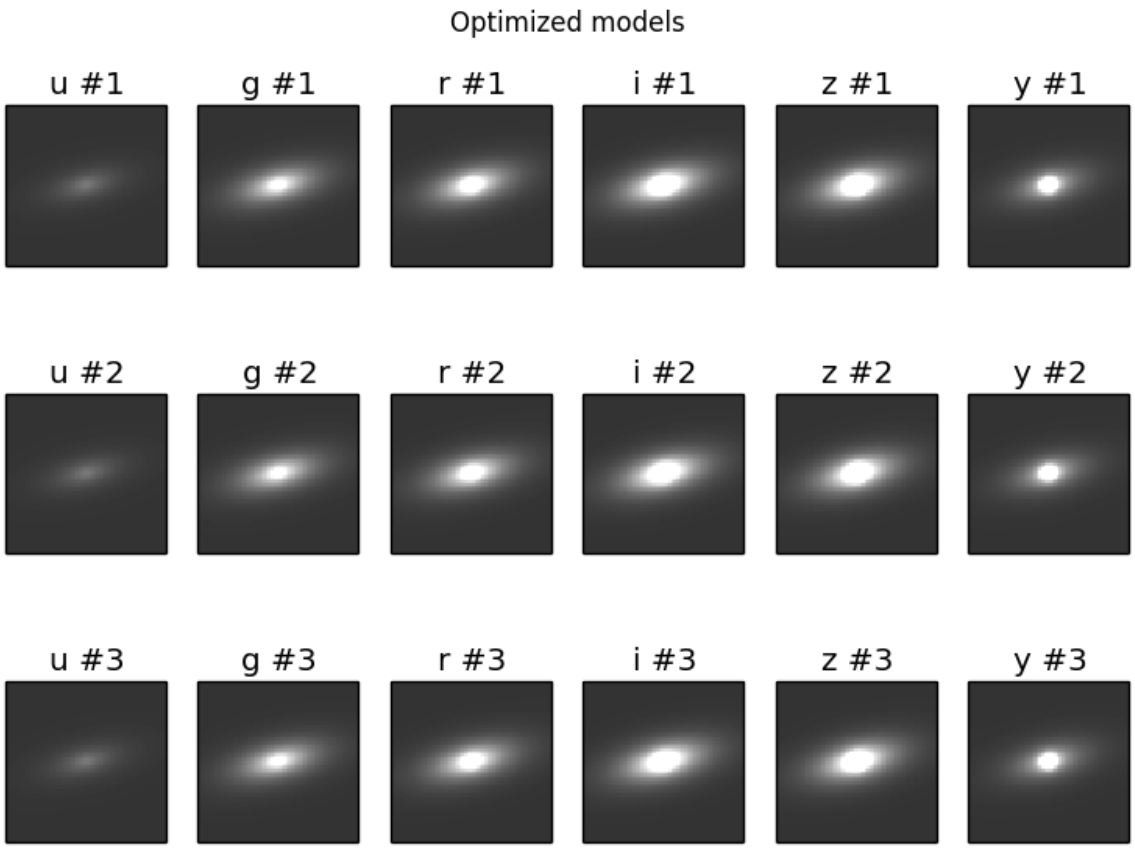
The resulting plots are:



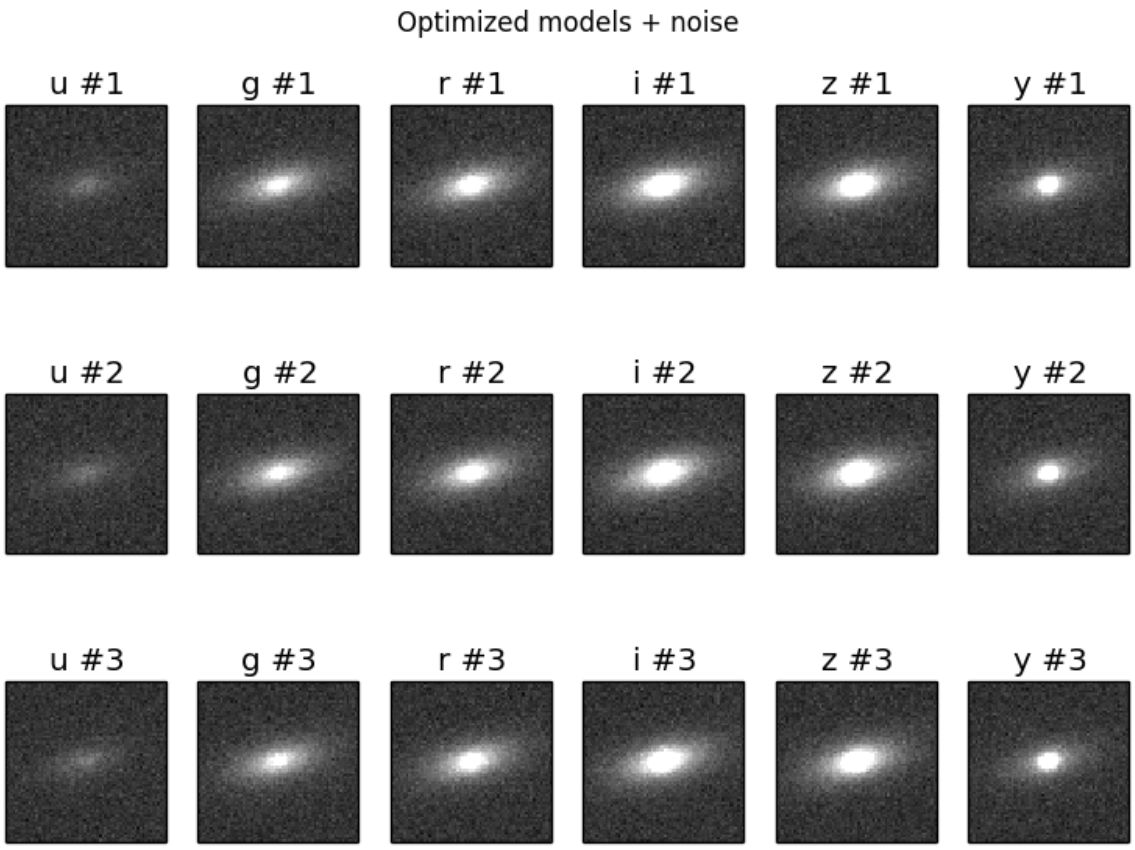
This is our terrible initial guess:



Here are the optimized models:



And here are the optimized models with the expected about of per-pixel noise added.


Optimized models + noise
u #1
g #1
r #1
i #1
z #1
y #1
u #2
g #2
r #2
i #2
z #2
y #2
u #3
g #3
r #3
i #3
z #3
y #3

CHAPTER 4

Code structure of the Tractor

Miscellaneous notes on control flow and call stacks.

```
Tractor.optimize()
    Tractor.getDerivs()
        Image.getParamDerivatives()
        Tractor.getModelImage()
        Tractor._getSourceDerivatives()
            Source.getParamDerivatives()
    Tractor.getUpdateDirection()
        Tractor.getChiImage()
        scipy...lsqr()
    Tractor.tryUpdates()
        Tractor.getLogProb()
```

```
Tractor.getLogProb()
     Tractor.getLogPrior()
     Tractor.getLogLikelihood()
         Tractor.getChiImages()
             Tractor.getModelImages()
                 Tractor.getModelImage()
                     Image.getSky()
                     Tractor.getModelPatch()
                         Tractor.getModelPatchNoCache()
                             Source.getModelPatch()
```

CHAPTER 5

Once-asked Questions

5.1 Q: My images have some crazy WCS that your code doesn't understand. What do I do?

My code looks like this:

```
from astrometry.util.util import Tan
from tractor import FitsWcs

wcs = FitsWcs(Tan('myimage.fits'))
```

and it's failing like:

```
blah
```

What do I do?

5.2 A:

One option is to create a `Tan` object yourself and populate it with the required parameters:

```
t = Tan()
t.set_crpix(24, 530)
t.set_crval(234.66, 47.8765)
t.set_cd(1., 0., 0., 1.)
t.set_imagesize(1024, 1024)
wcs = FitsWcs(t)
```

And you'll probably actually do that by opening your image file and parsing its crazy header cards, converting them to TAN as understood by our code:

```
import pyfits

hdr = pyfits.open('myimage.fits')[0].header

t = Tan()
t.set_crpix(hdr.get('CRPIX1'), hdr.get('CRPIX2'))
t.set_crval(hdr.get('CRVAL1'), hdr.get('CRVAL2'))
cd1 = hdr.get('CDELT1')
cd2 = hdr.get('CDELT2')
# assume your images have no rotation...
t.set_cd(cd1, 0., 0., cd2)
t.set_imagesize(1024, 1024)
wcs = FitsWcs(t)
```

CHAPTER 6

API Reference

- *Ducks* – code-as-documentation descriptions of the types of objects using by the Tractor
- *Utilities* – ParamList, MultiParams, other utility types
- *Basics for standard images & catalogs* – Types for standard images, magnitudes, WCSes
- *Core Tractor routines* – Core Tractor routines
- *Galaxies* – SDSS exp & deV galaxies
- *SDSS images & catalogs* – Specific data types for handling SDSS images and catalogs
- *CFHT images & catalogs* – Specific data types for handling data from the Canada-France-Hawaii Telescope

6.1 Flat list

- `Brightness`
- `CompositeGalaxy`
- `Catalog`
- `ConstantSky`
- `DevGalaxy`
- `ExpGalaxy`
- `FitsWcs`
- `Flux`
- `GaussianMixturePSF`
- `Image`
- `Images`
- `Mag`

- Mags
- MagsPhotoCal
- MultiParams
- NamedParams
- NCircularGaussianPSF
- NullPhotoCal
- NullWCS
- ParamList
- Params
- Patch
- PhotoCal
- PixPos
- PointSource
- PSF
- RaDecPos
- Sky
- Source
- Tractor
- WCS

6.2 Ducks

6.3 Utilities

6.4 Core Tractor routines

6.5 Galaxies

6.6 SDSS images & catalogs

6.7 CFHT images & catalogs

CHAPTER 7

Case Study: Extending the Tractor to do Strong Gravitational Lensing

This tutorial (really more of a case study) goes through extending the Tractor for a new kind of astronomical source. Hi, Phil!

We want to create a new kind of `Source` object: a strongly gravitationally lensed quasar. The lens will have a visible component: a `DevGalaxy` galaxy profile, as well as a dark component that defines its mass. The lens will produce 2 to 4 images of the quasar.

The lens model produces only approximate estimates of the brightness of the multiple quasar images, so we will need a "fudge factor" for the magnitudes predicted by the lens model.

We want to create a class to hold our Lensed Quasar:

```
from tractor import MultiParams
from tractor.sdss_galaxy import DevGalaxy

class LensedQuasar(MultiParams):
    @staticmethod
    def getNamedParams():
        return dict(light=0, mass=1, quasar=2, magfudge=3)
```

We chose to make it inherit from `MultiParams` because we want to think of it as being *composed* of the *light* (visible component of the lens that determines its appearance), *mass* (the dark mass of the lens that determines its lensing behavior), and the *quasar* being lensed. We also have *magfudge*, our fudge-factor for the quasar's brightness at each image.

We want our `LensedQuasar` to be a `Source` that can be manipulated by the Tractor, though. We therefore have to implement the interface described by `Source`; we have to make our `LensedQuasar` quack like a `Source` duck.

To do this, we add the methods defined in `Source` to our `LensedQuasar`:

```
from tractor import PointSource

class LensedQuasar(MultiParams):
    # ... as before ...
```

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```
    def getModelPatch(self, img):
        # We start by rendering the visible lens galaxy.
        patch = self.light.getModelPatch(img)

        # We will use the lens model to predict the quasar's image positions.
        positions,mags = self.mass.getLensedImages(self.light.position, self.quasar)
        # 'positions' should be a list of RaDecPos objects
        # 'mags' should be a list of Mags objects

        for pos,mag,fudge in zip(positions, mags, self.magfudge):
            # For each image of the quasar, we will create a PointSource
            ps = PointSource(pos, mag + fudge)
            # ... and add it to the patch.
            patch += ps.getModelPatch(img)

        return patch

    def getParamDerivatives(img):
        pass
```

In the `getModelPatch` method, we have to return a `Patch` object: a synthetic rendering of our `LensedQuasar` as it would appear in the given `Image`. We will do that by combining the appearance of `self.light` – the visible component of the lens – with the multiple images of the quasar whose positions and brightnesses are estimated by the lensing model, `self.mass`.

Now, what is the `mass` going to look like? It is going to have parameters that we want the Tractor to be able to optimize, so it has to be a `Params`. Actually, as you might have guessed, it just has to quack like a `Params`. Since our `mass` is just going to have a few parameters, we could inherit from `ParamList`:

```
from tractor import ParamList

class LensingMass(ParamList):

    @staticmethod
    def getNamedParams():
        return dict(mass=0, radius=1)

    def getStepSizes(self):
        '''We're using units of solar masses and arcsec'''
        return [1e12, 0.1]

    def getLensedImages(self, mypos, quasar):
        pass
```

The `getLensedImages` function is the one we're going to call from `LensedQuasar.getModelPatch()` to predict the lensed image properties.

Let's fill in the blanks and get the code to run. To create a `LensedQuasar` object, we'll have to create its components. We will mock up the `Quasar` and `MagFudge` classes. Currently `Quasar` doesn't even have any parameters, and that's ok:

```
from tractor import RaDecPos, Mags
from tractor.sdss_galaxy import GalaxyShape

class Quasar(ParamList):
    pass
```

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```
class MagFudge(ParamList):
    pass


if __name__ == '__main__':
    # Create properties of the lensing galaxy:
    pos = RaDecPos(234.5, 17.9)
    bright = Mags(r=17.4, g=18.9, order=['g','r'])
    # GalaxyShape( re [arcsec], ab ratio, phi [deg] )
    shape = GalaxyShape(2., 0.5, 48.)
    light = DevGalaxy(pos, bright, shape)

    mass = LensingMass(1e14, 0.1)

    quasar = Quasar()

    # Four parameters for up to four images.
    fudge = MagFudge(0., 0., 0., 0.)

    # Create a LensedQuasar object from its components.
    lq = LensedQuasar(light, mass, quasar, fudge)

    print 'LensedQuasar params:'
    for nm,val in zip(lq.getParamNames(), lq.getParams()):
        print '  ', nm, '=', val
```

and this will print:

```
LensedQuasar params:
   light.pos.ra = 234.5
   light.pos.dec = 17.9
   light.brightness.g = 18.9
   light.brightness.r = 17.4
   light.shape.re = 2.0
   light.shape.ab = 0.5
   light.shape.phi = 48.0
   mass.mass = 1e+14
   mass.radius = 0.1
   magfudge.param0 = 0.0
   magfudge.param1 = 0.0
   magfudge.param2 = 0.0
   magfudge.param3 = 0.0
```

CHAPTER 8

Using Ceres Solver with the Tractor

8.1 Building Ceres Solver

See http://ceres-solver.org/building.html

CHAPTER 9

API Reference – Tractor Basics

9.1 Basics for standard images & catalogs

9.1.1 Basic Image calibrations

Sky

The "Sky" describes the "background" in your images—what the images would look like in the absence of noise or astronomical sources.

Astrometry (World Coordinate System, WCS)

Photometry calibration ("PhotoCal")

Point-spread function (PSF)

9.1.2 Basic Sources

CHAPTER 10

Indices

- genindex
- modindex
- search