OasisPy Documentation

Release 1.0

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CHAPTER 1

Installing **OasisPy**

Getting **OasisPy** is easy.

For those with `pip`, simply fetch the package with:

```
$ pip install OasisPy
```

Upon installation you will be prompted with a few questions. The first is the path where **OasisPy** will place the **OASIS** directory, which contains the directory tree in which all of **OasisPy**'s image proccessing will take place. You can make this path anything you want, but to make it easier to find later it usually is best to stick with simple location like your **home** directory. The second prompt you will recieve will be asking if you would like to install the `ISIS` image subtraction program along with your **OasisPy** installation. The default to this is yes, and should always be so unless you know for a fact you have this software already installed on your machine.

1.1 System Requirements

OasisPy was developed on a Linux machine and must be run on a POSIX-compliant system.

1.2 Software Requirements

There are a number of outside programs **OasisPy** calls on that will need to be installed as well. Most of these are image processessing software written by Emmanuel Bertin and can be fetched from https://www.astromatic.net/.

- `SExtractor` (*astromatic*)
- `PSFex` (*astromatic*)
- `SWarp` (*astromatic*)
- `SkyMaker` (optional, used for simulations) (*astromatic*)
- `PyRAF` (recommended install through Anaconda)
- `ISIS` (automatically installed during **OasisPy** setup)

CHAPTER 2

Getting Started

2.1 OasisPy Basics

OasisPy is a collection of python modules that facilitate the OASIS difference imaging process. Each module is in charge of one step in the process. There are a total of 13 modules, and each can either be called individually or in succession, depending on the project at hand. We call these modules "**OASIS** methods."

- `initialize`- Sets up the **OASIS** environment. Is automatically run during install and will never have to be run again unless you want to duplicate or move the **OASIS** file tree.
- `get`- Downloads images from an online archive or finds images on the local hardrive and moves them into the **OASIS** file tree to be processed.
- `mask`- Masks cosmic rays, saturated stars, CCD defects, and any other artifacts that will inhibit the difference imaging process.
- `psf`- Computes a PSF model for each image in the data set. This model will be used in many of the subsequent steps.
- `align`- Chooses the highest S/N frame to be the "reference image," then registers all other images to this reference pointing (to subpixel precision).
- `combine`- Stacks images into a high S/N template frame to be used for subtraction.
- `subtract`- Subtracts the template from each image in the data set to create a set of residual frames. This is the most complex and computationally expensive step, and will take the longest to execute.
- `mr`- Stands for **m**aster **r**esidual. The residual images created with `subtract` are stacked to for a master residual frame.
- `extract`- Searches the residual images for sources of significant flux. Filters out non point source-like objects and other false positives. Outputs a complete source catalog with all detected variable objects, their position, and their total flux.
- `test`- Tests the installation of **OasisPy** by fetching a set of images of exoplanet HAT-P-37b and running them through the **OASIS Pipeline**.
- `simulation`- Allows further testing of the **OASIS Pipeline** through two different simulated data sets.

- `run`- Master method that facilitates access to all other methods.
- `pipeline`- The **OASIS Pipeline**, an all-in-one method that executes the entire difference imaging process, from `get` to `extract`.

For more information on each method and how **OasisPy** works see *How It Works*.

2.2 Using OasisPy

OASIS methods can be executed in two ways.

2.2.1 As A Python Module

The simplest way to use **OasisPy** is to treat each method like a simple python module and import them into directly into your code. If comfortable with scripting this is the recommended method of operation as it provides the user with the maximum amount of control over the difference imaging process.

Methods can be called within your python script with the following import:

```
from OasisPy import methodname
```

See *API* for the details on each method.

2.2.2 Shell Execution

Methods can also be run from the shell (ANSI) using the formula

```
$ oasis-methodname
```

For example, to align a set of images one would type

```
$ oasis-align
```

Each method has a certain number of input parameters the user must provide. Often this just consists of the location of the images being differenced. These parameters are provided by the user through input prompts executed after the initial calling of the method.

This shell execution of **OasisPy** was included to allow those not comfortable with scripting in python, specifcally undergradute or high school students with little or no coding experience, a relatively easy way to access the package's main functionalities.

2.3 Convenience Methods

Understanding what each of the 13 methods does is critical for complex projects and will allow you to get the most out of the software, but it is not mandatory. For many projects, all you may want to do is call a high level function to do all of the difference imaging steps for you. For this reason we have included several convenience functions for those that do not want to deal with the inner workings of **OASIS**.

2.3.1 Run

This is the most important convenience function to know. It can be thought of as the "main page" of **OASIS**, from which you can execute any other **OASIS** method. To call `run` simply type

```
$ oasis-run
```

in your terminal. A list of all possible **OASIS** methods is displayed, and from this list you can pick a command and type it into the prompt. It is reccommended to users new to linux and python that `run` be the only method directly used.

2.3.2 Pipeline

The `pipeline` convenience function makes up what is called the **OASIS Pipeline**. This is simply a conglomerate of every **OASIS** method into a single master method. Input data are fed into each method one-by-one and then piped to the next. Using `pipeline`, a user can send a set of images through the entire difference imaging process with a single high-level command, without worrying about what is actually being done in the intermediary steps. To execute it, type `oasis-pipeline` in the terminal or select 'pipeline' if using `run`.

CHAPTER 3

How It Works

Here we describe the inner-workings of the **OASIS** engine.

Note: This section is dedicated to showing the algorithms and theory behind **OASIS**. For a thorough step-by-step introduction to using **OasisPy** to process real images, see *this Jupyter notebook (TBW)*.

3.1 Overview of the Software

3.1.1 OASIS Environment

All of the **OASIS** image processing takes place in the **OASIS** environment, a file tree with containers that drive the **OASIS** engine. This set of directories is created automatically during install in the user-specified location, with the root directory being named **OASIS**. Shown below is a schematic of the file tree.

Warning: Once the **OASIS** file tree is created, DO NOT move or delete any of the three main directories. Manipulating these master directories will result in runtime errors.

3.1.2 The Difference Imaging Process

Difference imaging is a photometric techinque in which a high signal-to-noise "template" image is subtracted from some real "science" frame to reveal residual sources of flux indicative of variable stars, exoplanet transits, supernovae, etc.

In order to do this successfully, there are a number of image processing steps that need to be done to both the science and template images in order to guarantee an acceptable residual. This is the achille's heel of difference imaging. When the images are prepared correctly, the techinque can be extremely powerful and efficient. When the pre-subtraction steps are done incorrectly, the technique can produce residuals riddled with false sources and messy flux distributions.

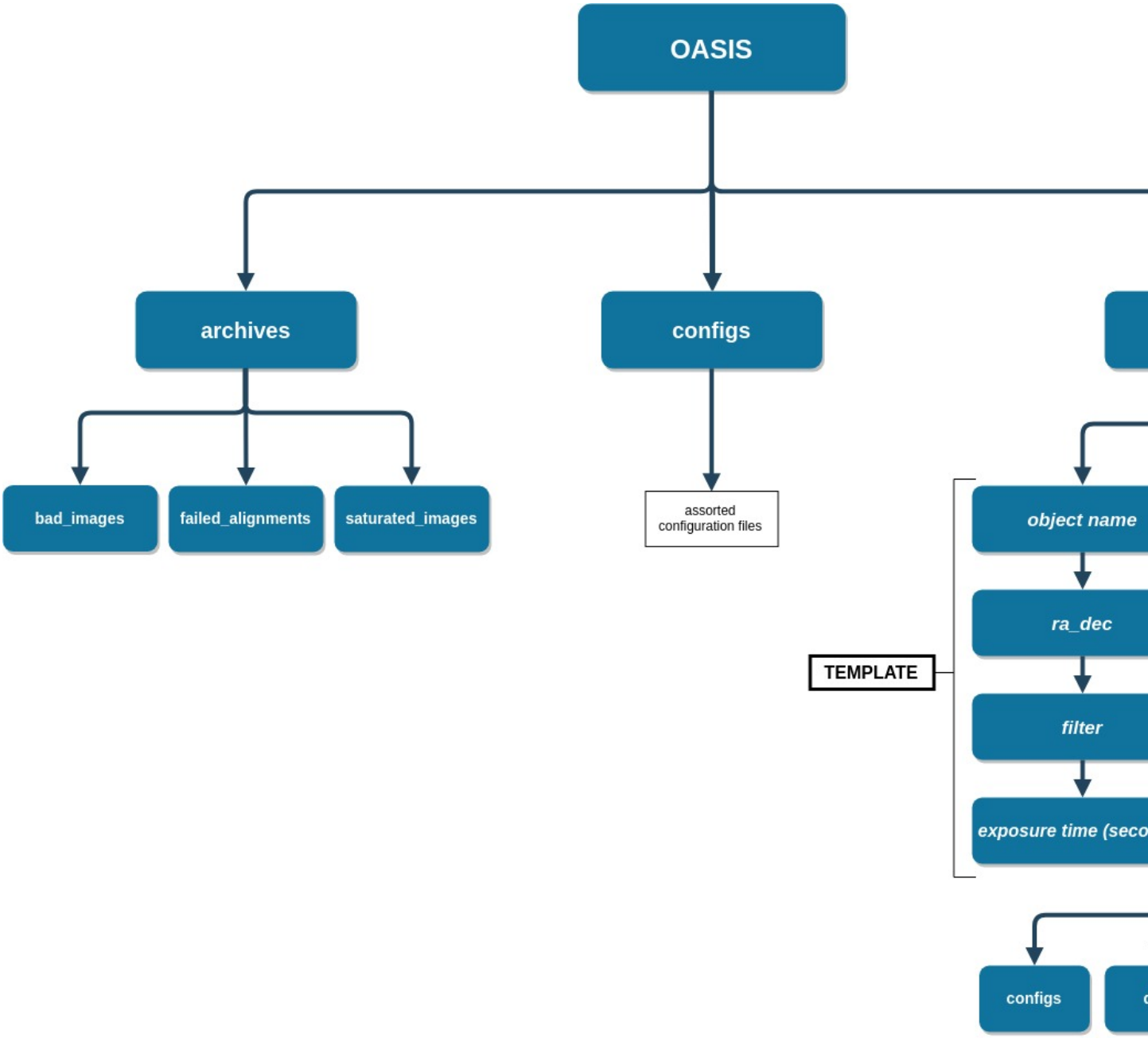


Fig. 1: Click image to enlarge.

Thus it is crucial that all steps in the difference imaging process are robust enough to work reliably with any type of astronomical CCD image. This is the main problem **OASIS** has attempted to solve.

The following sections will describe each of the aforementioned steps one must complete in order to difference two astronomical images. Below is a rough schematic of the **OASIS Pipeline** and its execution order.

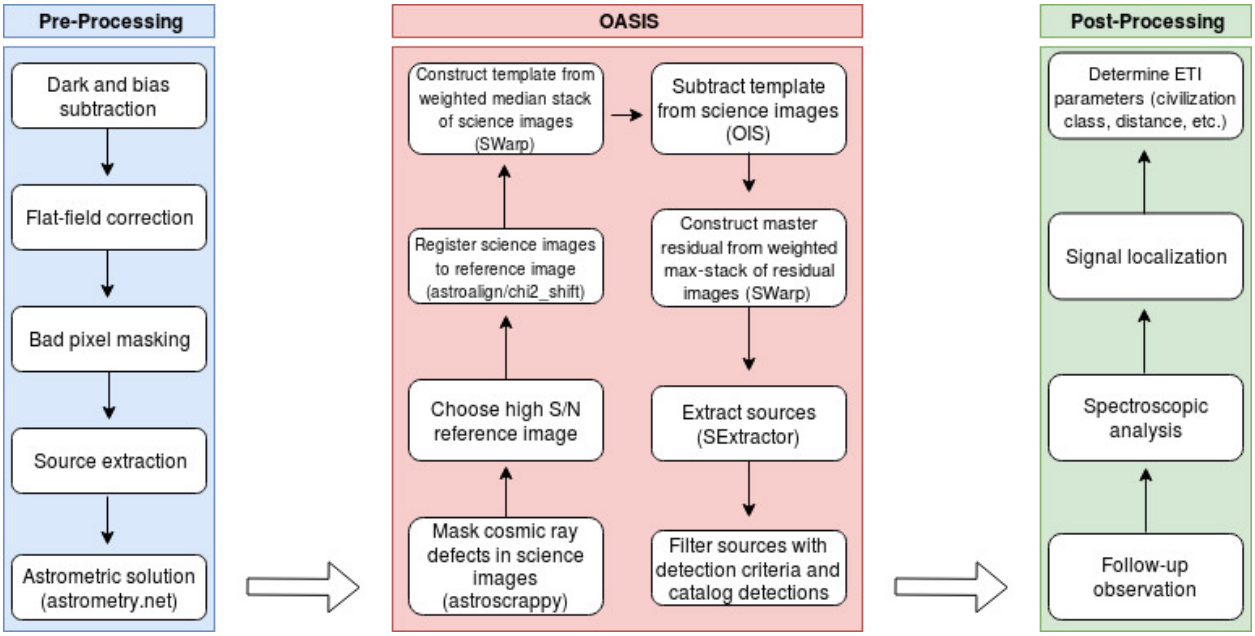


Fig. 2: Note that your "Pre-Processing" section may be different depending where you get your data from. The example above assumes the user has fetched data from the Las Cumbres Observatory online archive (LCO data archive).

Note:

A quick word about the language used in the following sections. There are numerous terms that appear often when discussing d

- **Science image**- All images in the data set. The science images contain the objects being sought.
- **Template image**- An image made by either stacking numerous science images or choosing a specific science image. This template is subtracted from each science image to look for variable objects.
- **Residual image**- The resulting image after the $Science - Template$ subtraction. The residual is a FITS image with identical dimensions, pixel scale, etc. to the original science images.
- **Source/Detection**- These terms refer to groups of adjacent pixels of high flux in the residual image that are indicative of some variable or transient object.
- **Subtraction artifact/false positive**- Detections that are the result of poor difference imaging or defects/noise unaccounted for during the calibration steps. Minimization of these artifacts is one of the foremost problems in difference imaging.

3.2 The OASIS Pipeline

3.2.1 Acquire Data

Before getting into the image processing, **OASIS** must first have images to process. **OasisPy** supports two data acquistion methods. The user can manually download their data from some repository and simply tell **OasisPy** where they're located on their local machine, or they can use the built-in `get` function to download images from Las Cumbres Observatory's (LCO) data archive. Of course, the second option is only useful if you are a LCO client or have a desire to analyze their publically available images

3.2.2 Masking

The first thing **OASIS** does with the input images is mask any problem areas. These include cosmic rays strikes, satellite trails, hot pixels, CCD defects, etc. This is a critical step in any difference imaging analysis as even the smallest artifact or set of bad pixels can inhibit the quality of the residual images.

Many observatories perform some of this masking automatically in their calibration pipelines, on-the-spot as data is taken. They often store these masks as FITS extensions to the original image. Consequently, before masking **OASIS** looks for a "bad pixel mask" (BPM) extension to use as a foundation for the mask building process. If none is found **OASIS** searches for another extension that might contain a mask. If this is unsuccessful the foundation is just a zero mask.

For the masking process **OASIS** makes use of a modified version of the `astroscrappy` python package (C. McCully), which itself is based off of the popular LA Cosmic algorithm. Running the `mask` method will mask all cosmic rays in each image, as well as saturated stars and other problem objects. Later on, edges created during the registration process are also added to this mask.

Note: There are two types of masks **OASIS** uses. The first is the common binary image mask, created during this masking process. In this type each pixel is represented by a 0 or 1, 0 being a good pixel and 1 being a masked one. The second type is what is usually referred to as a "weight-map." Here the elements of the map represent the weight of each pixel. Another way to think about it is as an inverse variance map. The higher a pixel's weight (or inverse variance) the more confident we are in the value of that pixel. Thus, bad pixels will have a low weight (usually 0) and good pixels will have a high weight (usually 1). The weight maps computed by **OASIS** are normalized on the interval [0, 1]. After the initial masking process all image masks are converted to weight maps, as these are more accurate and offer a greater amount of masking control. If you are ever uncertain on what type of mask an image has, just look for the 'WEIGHT' header keyword in the primary FITS header. A value of 'Y' means it's a weight map, a value of 'N' means it's a binary mask.

3.2.3 PSF Modeling

A critical step in any difference imaging application is being able to model the point-spread functions (PSFs) of the dataset quickly and accurately. **OASIS** does this using the Astromatic program **PSFex** (E. Bertin). The outputted models are then used by **OASIS** for a number of different operations. A preliminary bad image-rejection algorithm uses the PSF FHWM to clip images exceeding a certain threshold. The reference image selection algorithm also uses the FWHM to choose the reference image. The source extraction algorithm uses the overall PSF model to distinguish between stellar sources and galaxies. In the future the PSF model will also be used to optimize the subtraction parameters more efficiently (section **something**).

Running the `psf` method will output two files for each image, one *.cat* file and one *.psf* file, both into the **psf** directory. The *.cat* file is the source catalog used by **PSFex** to compute the PSF model. The *.psf* file is the PSF model itself.

3.2.4 Image Rejection

After masking and PSF modeling **OASIS** searches the dataset for poor quality images that will inhibit the difference imaging process. These usually include images with large defects, focusing issues, extremely poor seeing, low S/N, etc., that could prove toxic, especially to the construction of the template image. This step is completed automatically during the registration step and does not need to be called explicitly. Any bad images found are moved into the **archive** OASIS subdirectory.

3.2.5 Registration

Before subtracting two images, it is critical to register them to the same astrometric grid (align them), ideally to subpixel precision. To do this **OASIS** employs a two-step registration approach. First, an initial non-subpixel transformation is found with the feature-based python package `astroalign` (M. Beroiz). Once the images are aligned using `astroalign` the final subpixel registration is completed using the `image_registration` (A. Ginsburg) python package, which uses the cross-correlation method to find the horizontal and vertical pixel offsets between the two images.

When registering images, a reference image needs to be chosen to which all other frames will be aligned. This is done automatically by **OASIS** when the `align` method is executed. The chosen reference image is the one with the highest S/N. Another option for choosig the reference is that with the best seeing. This option may be included in a later version of **OASIS**.

After the reference frame is chosen and the registration is complete, the last step of the *align* method is to match the intensity scales of each image to the reference image. This step utilizes the **IRAF** routine `linmatch`. Here flux is preserved as the intensity offsets are assumed to be linear.

Note: After each image is registered, its filename will change from *timeofexposure_N_.fits* to *timeofexposure_A_.fits*. The "U" represents "unaligned" and "A" represents "aligned."

3.2.6 Template Construction

After the images are all masked and registered to the reference field, they are ready to be combined into a template image. This template image is simply a weighted median stack (according to their weight maps) of the science images images with the best seeing. The default number of images to include in the stack is top 33% with respect to seeing, though this can be changed in the *OASIS.congig* file. The actual stacking is done with the program **SWarp** (E. Bertin). The final template image is outputted to the target's 'templates' directory, along with a log of the past template constructions. This log is titled *log.txt* and is located in the **templates** directory.

3.2.7 Subtraction

Finally we arrive at the heart of **OASIS**. In this step the images will finally be subtracted from each other to create the residual frames that will be searched for variable objects.

OASIS handles the subtraction in two different steps. The first is the actual subtraction of the images, and the second is quality assurance, making sure that all the residual frames represent a successful subtraction. Both steps are included in the `subtract` method, so no explicit calls need to be made to either one.

Step One

The first subtraction step starts with all science frames again having their flux rescaled, this time according to the template image. This is again done with **IRAF**'s `linmatch` routine. After this rescaling each science image's header

will have the keyword 'SCALE' value changed to 'Y'. Next **OASIS** calls upon the **ISIS** program (C. Alard), which implements the popular Optimal Image Subtraction (OIS) algorithm. The main goal of OIS is to smear the template's PSF to exactly match the science's PSF. This is done through the use of a convolution kernel made up of a set of basis vectors (found using a least squares approximation), which is then applied to the template image. OIS handles the matching of both the backgrounds and the PSF, with the option for deriving a spatially-varying kernel. This is crucial as especially with large-scale survey data, the PSF is almost certain to vary across the image plane. Without this step there will be significant errors in the residual images and thus false positives in the source extraction step. There are numerous user-defined parameters OIS uses to complete this. This is **OASIS**'s most computationaly intensive test. It takes a few seconds for each PSF to be matched, and up to 45 seconds per image if no optimal configuration setup is found (see subtraction step two). After the PSFs of the two image are matched the template is subtracted from the science image and the output residual image is placed in the **residuals** directory with the *_residual_* suffix appended to the end of the original image name.

Step Two

The second subtraction step (the "optimization") ensures that each residual created in the first step is the best possible subtraction. This is done by first checking the quality of the residual obtained in the first step, then repeating the step with a different OIS configuration set until the optimal residual is created. The OIS configuration set is a text file defining a number of parameters that will be called by the subtraction algorithm. They define things like the size of the stamp (the pixel box used to search the image for stars), the degree of PSF variation across the image, the size of the kernel used to convolve the template PSF, etc. The optimal values for these parameters vary depending on the type of image being subtracted. For most images, the default values for these parameters will work fine. On some images though, especially if they're extremely oversampled or undersampled, a different set of values must be used. This is where the optimization step comes in. It tries running the subtraction program with a variety (a set of 9) of common parameter values, checking each time if the subtraction is up to an acceptable quality. When it finds the correct confguration, that residual is kept and OASIS moves onto the next image. In the unlikely event that no good configuration is found, the residual is completely masked so as to prevent contaminating the master residual frame.

Residual Quality

The most important part of the "optimization" step described above is the checking of the residual's quality. Deriving a rigorous quality-estimation algorithm is paramount to the ability of **OASIS** to choose the "best" residual.

To calculate the "goodness" of each residual frame, **OASIS** takes a simple minimization approach. First, the ideal residual frame is found for the given science and template images. This ideal residual is defined to be the result of subtracting two Poisson-distributed noise images, each with a mean pixel value equal to the background of the original input images. These Poissian noise images represent ideal science and template images, free of CCD noise and defects, and free from any sources. These images are then limited only by the photon shot noise instrinsic to all astronomical observations. This shot noise follows a Poissonian distribution with a mean approximately equal to the average background pixel value in photons. Subtracting these two shot noise images results in the "ideal" residual frame, a shot noise-limited image free of any artifacts, defects, sources, and additional noise.

Mathematically this ideal residual can be decribed by the Skellam distrubtion, which is defined as the probability distribution of the difference of two random variables that both follow the Poissonian distribution. This probabiltiy distribution has the form

$$p\{k; \mu_S, \mu_T\} = e^{-(\mu_S+\mu_T)}(\mu_S/\mu_T)^{k/2} I_k(2\sqrt{2\mu_S\mu_T})$$

where μ_S and μ_T are the mean background photon counts of the science and template images, respectively, and I_k is a modified Bessel function of the first kind. The mean of this Skellam-distributed residual μ_R is simply $\mu_R = \mu_S - \mu_T$ and its standard deviation is $\sigma_R = \sqrt{\mu_S + \mu_T}$. This is the distribution the real residuals should follow as closely as possible. Therefore, one way to estimate the quality of a given residual is to measure the residual's deviation from this ideal Skellam distrubtion. **OASIS** does this by using this ideal Skellam image to compute a "quality parameter" Q.

More details on the Q metric can be found in the software's accompanying paper (**citation**), but briefly it is defined as

$$Q = 1/(1 + [\chi^2/N_{pix}])$$

where χ^2 is the standard chi-squared value from the "goodness-of-fit' test of the ideal Skellam distribution and the real residual's pixel distribution, and N_{pix} is the number of pixels used to fit the two distributions. N_{pix} is included in the expression as a sort of "normalizing" factor" to keep χ^2 at a reasonable value. The number of pixels used to calculate Q is often extremely large, usually well over a million, which has the tendancy to inflate χ^2 values for residuals that otherwise would be considered perfect. Dividing χ^2 by N_{pix} accounts for this inflation.

The metric Q is defined in this way in order to facilitate clipping of poor quality residuals. By definition, $Q > 0.50$ indicates a good residual, and $Q = 1$ indicates an unobtainably perfect one. These are robust values that should be true for most astronomical data, though the time may come when the user wants to choose theri own thresholding values.

Two thresholds are defined by **OASIS** in order to choose the best residual, a *floor* threshold and *ceiling* threshold. The *floor* threshold resresents the minimum Q value a residual can have and still be accepted by **OASIS**. The *ceiling* threshold is the Q value that when exceeded, the optimization step is stopped and the current residual is taken to be the best. As a default setting **OASIS** uses a *floor* Q value of 0.50 and *ceiling* of 0.75. These thresholds can be changed by editing the *OASIS_configs.txt* file in the **configs** directory, but be warned, if they are made to be too low the risk of false sources being included in the final object catalogs increases, and if they are made too high the program's runtime may increase to a point of absurdity, possibly up to 5 minutes for a single science-template image set. The default thresholds represent a good compromise between these two cases. Even so, if your project is exceptionally unique you may benefit from playing with the Q thresholds.

3.2.8 Source Extraction

The final step in the **OASIS Pipeline** is to extract any sources from the residual frames created in the previous `subtract` step. If the subtraction is done correctly, theoretically the residual images should be photon noise-limited, meaning that the dominant source of flux is simply the photon noise present in the original science and template images. This noise cannot be subtracted away and will thus make up a uniform "background" of the residual image. Source extraction then becomes a trivial process, simply looking for groups of adjacent pixels exceeding a certain ADU threshold, identical to the problem of source extraction in regular stellar images. Due to this, rather than reinvent the wheel, OASIS calls on popular source extraction software used for this very purpose–**SExtractor** (E. Bertin).

SExtractor has a large swath of tunable parameters that can be changed to make the program work for a wide range of data. Most of these parameters will never need to be changed, and those that do are automatically updated for each image by **OASIS**. However, you may wish to change the parameters configuration yourself, especially if your images are unique in some way. To do this simply edit the *default.sex* file in the **configs** directory.

The structure of the `extract` method is as follows:

1. First, the residual frames are all normalized according the a statistic called the *poisson deviation*. The poisson deviation is simply the combined photon shot noise of the original science and template image. Mathematically the normalization can be expressed as $R_{norm} = (R - \mu_R)/\sqrt{B_S + B_T}$, where R is the original residual image, μ_R is the residual's mean pixel value, and B_S and B_T are the sigma-clipped background estimates for the science and template images, respectively. If the residual is a quality one, this normalization will result in a pixel distribution closely resembling a standard normal curve.

2. After normalization, a stack of the residuals is constructed using the weighted average of each pixel value. This image stack is called the *master residual*, and it is currently an experimental feature. Stacking residual frames can be a extrmemely valuable for a number of reasons. For one, it makes quick identification of variable stars and transient objects easy. Rather than sift through the catalogs of hundreds or thousands of images, one can simply look at a master residual frame to find all of the sources in question. Of course, this means sacrificing the source's temporal information (time of detection), but sometimes just knowing a signal exists is all a user needs to do. Additionally, creating a master residual is enticing because of the S/N increase that is possible when stacking astronomical data. Sources that would otherwise be too faint to be detected by **SExtractor** in

their individual residual frames could possibly become visible in the master frame due to the minimization of background noise. However, as good as it is to have a master residual, implementing this stacking successfully is tricky and has the potential to do more harm than good. The primary difficulty in creating the master residual is deciding on a stacking algorithm. A historically popular choice has been to stack the residuals according to the sum of squared pixel values. This is an effective algorithm as it is incredibly sensitive to outliers (sources), however we have found that it is also prone to false positives. This is because bright stars will sometimes leave residual flux primarily due to scintillation. This residual is not detected as a signal in the individual residual image because of its noisy profile, but when the images are all stacked this bright star residual will often combine to form a point source object, which **OASIS** then mistakes for a variable star. This was verified using simulated, non-variable data (see paper for the more gory details). A safer option for stacking is the weighted mean. It is less sensitive to outliers and thus decreases the source S/N, but it also minimizes the number of false positives leaking into the master residual. This is the default stacking method OASIS uses, and has proven to be fairly reliable. However, it is advised to still use caution when looking at your master residuals, and when in doubt as to whether a certain signal is authentic or not we suggest taking a look at the individual residual source catalogs for verification.

3. After normalization and residual stacking, **SExtractor** can finally be run. First **SExtractor** is run on each individual residual image, generating a preliminary source catalog for each. **SExtractor** is then run on the master residual, outputting another catalog when completed.

4. The final step of the `extract` method is source rejection. In its first run through the data, **SExtractor** will inevitably record many "sources" that are not real sources at all. Most of these will be cosmic rays or hot pixels that evaded **OASIS**'s masking step, bright or saturated star residuals, or satellite/asteroid trails. Thankfully, all of these possess a different profile than a true variable point source, and thus are easly filtered out. To do this **OASIS** implements a filtering algorithm, the steps of which will be briefly laid out here.

    - Sources that show up in a majority of the residual frames are rejected
    - Sources that are diveted (a sign of saturation or subtraction error) are rejected (see paper for details)
    - Sources with a `spread_model` parameter less than 0 or greater than 0.1 are rejected.

After the initial catalogs are cut down by the above filters, the remaining sources are compiled into one master catalog titled *filtered_sources.txt* located in the **sources** directory. The unfiltered sources can be found in the *sources.txt* file.

After the individual residuals are "SExtracted", filtered, and cataloged, the master residual will undergo the exact same process. The outputted catalogs for the master residual are *MR_filtered_sources.txt* and *MR_sources.txt*.

In addition to these final catalogs **OASIS** outputs a file called *total_sources.txt*. This text file includes some basic statistics of the dataset's source catalogs. Specifically, it shows the number of initial sources found by **SExtractor**, the number that were filtered out, and the number of remaining "confirmed" detections in both the individual residuals and the master resiudal. It also shows the number of images that were not able to be subtracted, as well as the dataset's average Q value.

Note: There are other more efficient filtering methods that can and should be included in this step. These include MCA (*morphological component analysis*) and a machine learned point-source classifier (*DES DiffIm pipeline*). Another possible filtering method uses edge and contour deteciton algorithms to distinguish between actual point sources and those resulting from bright/saturated stars. All of these implementations are under development and at least one will be included in the next release of **OASIS**.

3.2.9 Simulations

Included in the **OasisPy** package is the ability to create simulated data sets to test and visualize **OASIS**'s efficacy. There are two options for running simulations, *fakes* and *zero-point*, both of which will be explained here.

- The *fakes* simulation superimposes fake point sources (fakes) onto a random image in your dataset, then runs the data through the **OASIS Pipeline**. This means of course to run this simulation a user needs to already have some data at their disposal. The final catalogs are then searched for the original fakes. A log of the detection statistics of the fakes is kept and used to create a detection efficiency plot at the end of the simulation. The fakes by nature of the code will be placed at random locations in the image plane with a random flux. The user can specify how many fakes to create, the range of possible fluxes, how many iterations of the simulation to run through, etc. The idea behind this simulation is to gauge the minimum flux a signal would need to be detected in a certain dataset. See paper and *API* for more details.
- The *zero-point* simulation involves taking a real image from a dataset, creating N simulations of the image, then running the simulated images through the **OASIS Pipeline**. The simulated images (zero-point images) are created using **SExtractor** and **SkyMaker** (astromatic simulation software). These zero-point images are made to all possess the same sources with all the same flux, hence the "zero-point" identifier. The only changes that are made to the simulations are the following

    1. Image is shifted and rotated by a random pixel offset and rotation angle
    2. Image seeing is degraded or sharpened slightly by a random seeing factor
    3. Image background is rescaled to a different, random value.

These manipulations are meant to mimick the frame-by-frame variations in real astronomical data. Thus the *zero-point* simulation tests **OASIS**'s ability to handle variations in PSF, background, and pointing, while still returning reliable difference imaging results. Since all zero-point images contain the same sources with the same flux, a successful simulation run would be one that returns zero variable sources in the *filtered_sources.txt* file. If the number of detection is higher than just a few, this is a sign that OASIS is not working properly. Users are encouraged to play with this feature to test the software's limits.

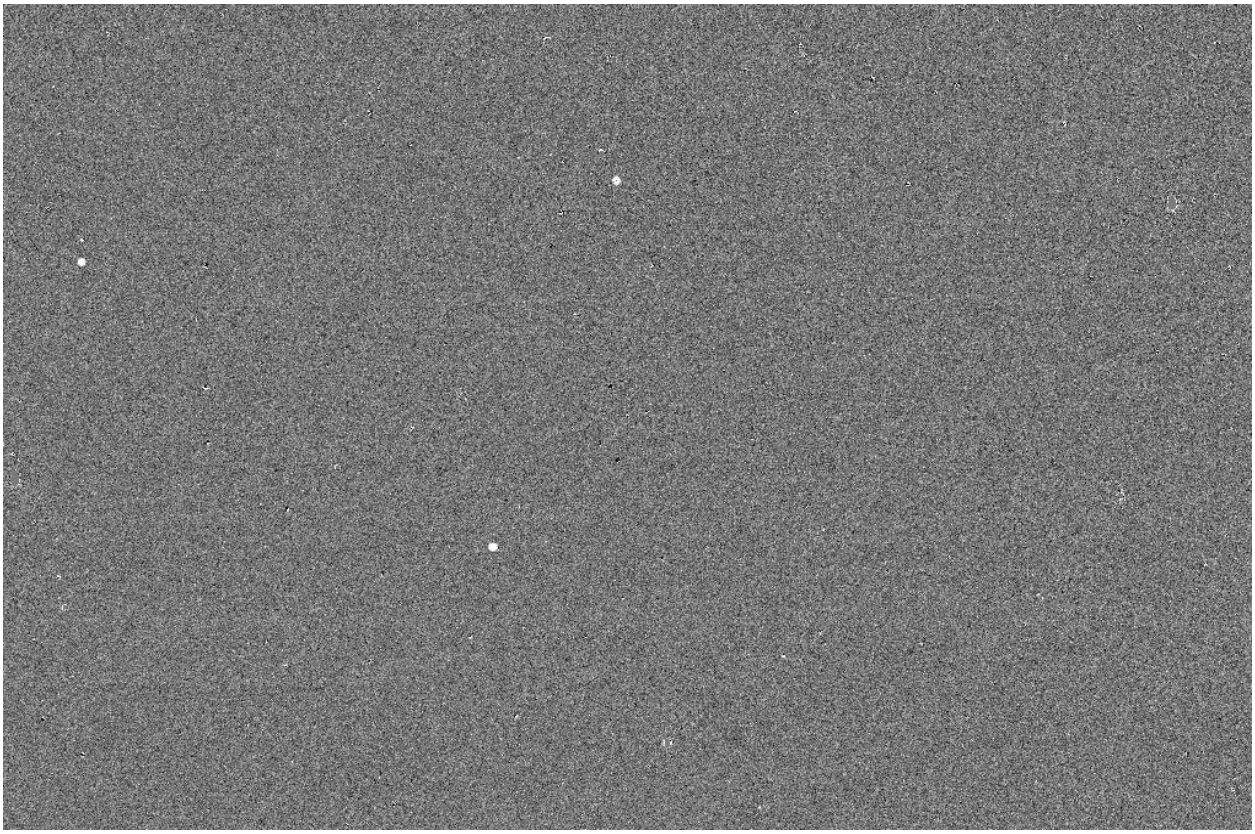
3.2.10 Mosaicking

OasisPy has a built in utility for users wanting to stitch together frames of adjacent pointings, likely survey data. Mosaicking this data into a single image can help uncover large-scale patterns in the difference images–such as distribution of variable stars in a spiral galaxy–or simply help to create pretty, presentation-worthy pictures.

The actual mosaic code is nothing more than a simple Python script written to faciliate the use of **Montage**, an astronomical mosaicking engine. **Montage** is essentially a collection of image processing modules that allow users to register and resample images, background match them, and create a mosaic (among many other things). The software is written in C, but interfacing with Python is easy with **MontagePy**, a collection of Python binary extensions to the existing **Montage** modules. Using **MontagePy**, we have written a simple Python script that takes a dataset and outputs the corresponding mosaic. The script is fairly robust, with the user being given control over many of the mosaicking parameters. Still, this is a bare bones mosaickig solution, and for more complicated or niche projects you are better off building your own personal implementation of **Montage**. For more info see the **Montage** documentation at http://montage.ipac.caltech.edu/.

3.2.11 Testing

To test the installation **OasisPy** includes a `test` method. This code downloads publically available data from the Las Cumbres Observatory's Science Archive, runs it through the **OASIS Pipeline**, then compares the obtained results with a set of control results. The object currently used to conduct the test is exoplanet HAT-P-37b. A total of 30 images are downloaded, and to illustrate **OASIS**'s ability to find transient objects three fake sources are added to image *02:59:10.860_A_.fits*. Looking at this image's residual or the data set's master residual should show these fake sources clearly. If successful the program will print out "TEST SUCCESSFUL!" at the conclusion of the test. Below is the control residual used for comparison. Clearly visible are the three fake sources.



CHAPTER 4

Tutorial

CHAPTER 5

Troubleshooting

CHAPTER 6

API

6.1 OASIS Methods

OasisPy.initialize.**INITIALIZE**()
Sets up the **OASIS** environment on a new machine. Creates the **OASIS** file tree and installs Alard's ISIS program (see documentation for details).

OasisPy.get.**GET**()
Fetches and prepares data for difference imaging. Two get modes:

- *dl*: used to fetch images from the Las Cumbres Observatory (LCO) data archive.
- *unpack*: used for non-LCO data. Users acquire images themselves and then call get in *unpack* mode to prepare the data for difference imaging.

OasisPy.mask.**MASK**(*path*)
Masks all cosmic rays, saturated stars, and other defects in the science images. Combines the cosmic ray mask with the image's initial bad pixel mask (set to NULL if no BPM is found) to make a master mask. Uses the python package astroscrappy (see documentation for details).

Parameters **path** (*str*) – Path of data file tree (contains the **configs**, **data**, **psf**, **residuals**, **sources**, **templates** directories). Use a comma-separated list for mapping to multiple datasets.

Returns All science images are masked. The values of the MASKED keyword in their FITS headers are changed to 'Y' if masking is successful.

OasisPy.align.**ALIGN**(*path*, *align_method='standard'*)
Registers all science images to their reference image. If no reference image exists, one is chosen (see documentation for details).

Parameters

- **path** (*str*) – Path of data file tree (contains the **configs**, **data**, **psf**, **residuals**, **sources**, **templates** directories). Use a comma-separated list for mapping to multiple datasets.
- **align_method (default='standard')** (*str*) – Method of alignment. Can be either *standard* or *fakes*. Default is *standard*. The *fakes* method should be used only for

simulations, as it bypasses registration and only performs photometric alignment.

Returns Aligns all science images are aligned to the reference image to subpixel precision. A succesful alignment changes an image's suffix from *_U_* to *_A_*.

OasisPy.psf.**PSF**(*path*)

Computes PSF model of science images. Uses PSFex (Bertin).

Parameters **path** (*str*) – Path of data file tree (contains the **configs**, **data**, **psf**, **residuals**, **sources**, **templates** directories). Use a comma-separated list for mapping to multiple datasets.

Returns PSF models of each science image are ouputted into the **psf** directory with the *.psf* suffix.

OasisPy.combine.**COMBINE**(*path*)

Stacks science images into a high *S/N* template frame. Stacking method is the weighted median value of each pixel and is done by the AstrOmatic software SWarp (E. Bertin). Only the top third of science images with respect to seeing are included in the template.

Parameters **path** (*str*) – Path of data file tree (contains the **configs**, **data**, **psf**, **residuals**, **sources**, **templates** directories). Use a comma-separated list for mapping to multiple datasets.

Returns Weighted median coaddition of all science images is outputted into the **templates** directory with the name convention of *StackMethod_NumberOfImagesInDataset.fits*.

OasisPy.subtract.**SUBTRACT**(*path*, *method='ois'*, *use_config_file=True*)

Performs difference imaging on the science images. The template image is convolved to match the science image's PSF, then the template is subtracted from the science image. This process is repeated for a number of different parameter configurations until an optimal residual is found. The actual convolution and subtraction is done with either the ISIS package (Alard) or hotpants (Becker). See documentation for details.

Parameters

- **path** (*str*) – Path of data file tree (contains the **configs**, **data**, **psf**, **residuals**, **sources**, **templates** directories). Use a comma-separated list for mapping to multiple datasets.
- **method** (*str*) – Method of difference imaging.
  - *ois* (default): Optimal Image Subtraction. Christohpe Alard's ISIS package.
  - *hotpants*: Andrew Becker's hotpants program. Very similar to Alard's OIS, but differs in input parameters. May be useful to try if OIS is returning inadequate results.
- **use_config_file (default=True)** (*bool*) – If True all input parameters are fetched from the local *OASIS.config* file.

Returns All science images are differenced and the corresponding residuals are placed in the **residuals** directory with the *_residual_* suffix.

OasisPy.MR.**MR**(*path*, *method='swarp'*, *sig_thresh=4*, *gauss_sig=3*, *gauss_filt=False*, *use_config_file=True*)

Stacks residual frames into a *master residual*. Extremely useful for identifying faint variables and quick object detection, but should be used with caution. See documentation for details.

Parameters

- **path** (*str*) – Path of data file tree (contains the **configs**, **data**, **psf**, **residuals**, **sources**, **templates** directories). Use a comma-separated list for mapping to multiple datasets.
- **method** (*str*) – Stacking method.
  - *swarp* (default): Uses SWarp (Bertin) to stack the residuals according to the weighted average of the pixels.
  - *sos*: Sum of squares, pixel-wise.

  - *sos_abs*: Absolute sum of squares, pixel-wise. Preserves sign. Mathematically, this look like $\Sigma(p_i \cdot |p_i|)$ with p_i being the ith pixel. For example, a series of pixels [10, 2, -3, -6] would be stacked according to 100 + 4 + -9 + -36.
  - *sigma_clip*: Takes the median of each pixel, unless there exists a pixel above or below a certain number of sigmas, in which case this outlying pixel is taken to be the stacked value.

- **sig_thresh (default=4)** (*float*) – Only used for *sigma_clip* method. Number of sigmas pixel must exceed to be used as stacked value.
- **gauss_sig (default=3)** (*float*) – Only used for *sigma_clip* method. Number of sigmas used for gaussian filter.
- **gauss_filt (default=False)** (*bool*) – Only used for *sigma_clip* method. When `True` the final master residual will be smoothed with a gaussian filter with a sigma equal to *gauss_sig*.
- **use_config_file (default=True)** (*bool*) – If `True` all input parameters are fetched from the local *OASIS.config* file.

Returns A stacked master residual frame, located in the **residuals** directory with the name *MR.fits*.

`OasisPy.extract.`**`EXTRACT`**(*path*, *method='both'*)

Extracts sources from individual residual frames located in **residuals** directory. Automatically filters out false positives and objects not of interest (see documentation for details). Uses `SExtractor` to create the initial sources catalogs, which are outputted to the **sources** directory.

Parameters

- **path** (*str*) – Path of data file tree (contains the **configs**, **data**, **psf**, **residuals**, **sources**, **templates** directories). Use a comma-separated list for mapping to multiple datasets.
- **method** (*str*) – Method of source extraction. Tells **OASIS** whether to extract sources from the individual residuals, the master residual, or both.
  - *both* (default): Runs `SExtractor` on both residuals and master residual.
  - *indiv*: Runs `SExtractor` only on residuals.
  - *MR*: Runs `SExtractor` only on master residual.

Returns A filtered source catalog for each image specified with the *method* parameter is created and appended to the text file *filtered_sources.txt* located in the **sources** directory. Source extraction statistics and extra info are located in *total_sources.txt*.

6.2 Convenience Functions

`OasisPy.pipeline.`**`PIPELINE`**(*path*)

The **OASIS Pipeline**. Runs all **OASIS** functions in succession.

Parameters **path** (*str*) – Path of data file tree (contains the **configs**, **data**, **psf**, **residuals**, **sources**, **templates** directories). Use a comma-separated list for mapping to multiple datasets.

Returns All-in-one difference imaging pipeline. Raw science images are placed in the **data** directory, and residual images and source catalogs are outputted into the **residuals** and **sources** directories, respectively.

`OasisPy.run.`**`RUN`**()

Master run function. Allows user to call any of the main **OASIS** methods. See documentation for details.

6.3 Auxillary Functions

OasisPy.simulation.**sim_fakes**(*location*, *n_fakes*, *iterations*, *input_mode='flux'*, *PSF='moffat'*, *subtract_method='ois'*, *f_min=0*, *f_max=40000*)

Simulates transient signals (fakes) and tests **OASIS**'s ability to detect them. The procedure of the simulation is as follows:

1. Makes a copy of the specified data set and moves it to the **simulations** directory.
2. Chooses a random image out of the data set and adds in fakes.
3. Runs the data set through the **OASIS Pipeline**.
4. Outputs a catalog of all fakes and whether or not they were detected.
5. Simulation is repeated with a different set of fakes.

Parameters

- **location** (*str*) – Path of data file tree (contains the **configs**, **data**, **psf**, **residuals**, **sources**, **templates** directories). Use a comma-separated list for mapping to multiple datasets.
- **n_fakes (default=20)** (*int*) – Number of fakes added to the chosen image.
- **iterations (default=50)** (*int*) – Number of iterations the simulation goes through. The total number of fakes added is then $n\_fakes \cdot iterations$. It is reccommended to choose *n_fakes* and *iterations* such that the total number of fakes is high, at least a few hundred, ideally more than 1000.
- **input_mode** (*str*) – How to interpret fake's flux parameter.
  - *flux* (default): Fake's brightness is assumed to be total flux of the fake in ADU and is determined by *f_min* and *f_max* parameters.
  - *mag*: Fake's brightness is given in magnitudes instead of ADU flux. *f_min* and *f_max* are then assumed to be apparent magnitudes rather than ADU counts.
- **PSF** (*str*) – Type of PSF model used for fake construction. See documentation for details.
  - *moffat* (default): Fakes are convolved with a 2D Moffat kernel.
  - *gaussian*: Fakes are convolved with a symmetric 2D Gaussian kernel.
- **subtract_method (default='ois')** (*str*) – Subtraction method used, can be either *ois* or *hotpants*, default is *ois*. See `subtract` method's documentation for details.
- **f_min (default=0)** (*float*) – Minimum flux for fakes. Assumed to either be given in ADU counts or apparent magnitudes depending on *input_mode*.
- **f_max (default=40000)** (*float*) – Maximum flux for fakes. Assumed to either be given in ADU counts or apparent magnitudes depending on *input_mode*.

Returns Catalog of all fakes, the image they were added to, iteration, and whether or not they were detected. See documentation for details.

OasisPy.simulation.**sim_sameField**(*location*, *numIms=100*, *bkg_mag=22.5*, *fwhm_min=3*, *fwhm_max=6*, *rot_min=-2.5*, *rot_max=2.5*, *shift_min=-2*, *shift_max=2*, *scale_mult=(0*, *1.5)*, *scale_add=(-20*, *50)*, *zero_point=25*, *mode='gauss'*)

Test **OASIS**'s ability to handle frame-by-frame variations in astronomical data and filter out false-positive sources. The procedure of the simulation is as follows:

1. Copies a random science image from the specified dataset to the **simulations** directory.
2. A source catalog of the chosen science image is made, containing information on each source's centroid location and total flux.
3. Using this source catalog, simulations of the chosen science image are made, all with constant source flux and location, but with different backgrounds, seeing, and pointing.
4. The set of simulated images are sent through the **OASIS Pipeline**.
5. Low numbers of detected sources signifies a successful simulation. There are no variable objects in the simulated images, so ideally zero sources should be detected by **OASIS**.

Parameters

- **location** (*str*) – Path of data file tree (contains the **configs**, **data**, **psf**, **residuals**, **sources**, **templates** directories). Use a comma-separated list for mapping to multiple datasets.
- **mode (default='moffat')** (*str*) – Simulation mode. Method by which simulated images are made. All images are given a uniform background, then smeared according to Poisson statistics.
  - *moffat* (default): Sources are convolved with a 2D Moffat kernel.
  - *gauss*: Sources are convolved with a symmetric 2D Gaussian kernel.
  - *real*: The actual PSF model of the chosen science image is used as the convolution kernel.
  - *sky*: AstrOmatic program `SkyMaker` (Bertin) is used to make simulated images.
- **numIms (default=100)** (*int*) – Number of simulated images to make.
- **bkg_mag (default=22.5)** (*float*) – Average background level in mags. Actual simulated background levels are chosen to be a random value within the interval $[bkg\_mag - 1.5, bkg\_mag + 1.5]$.
- **fwhm_min (default=3)** (*float*) – Minimum FWHM of simulated images in pixels.
- **fwhm_max (default=6)** (*float*) – Maximum FWHM of simulated images in pixels.
- **rot_min (default=-2.5)** (*float*) – Lower bound on angle of rotation in degrees.
- **rot_max (default=2.5)** (*float*) – Upper bound on angle of rotation in degrees.
- **shift_min (default=-2)** (*float*) – Lower bound on (X,Y) shift in pixels.
- **shift_max (default=2)** (*float*) – Upper bound on (X,Y) shift in pixels.
- **scale_mult (default=(0,1.5))** (*tuple*) – Interval of acceptable multiplicative scale factors.
- **scale_add (default=(-20,50))** (*tuple*) – Interval of acceptable additive scale factors.
- **zero_point (default=25)** (*float*) – Zero point magnitude.

Returns Standard **OASIS Pipeline** output, residual frames located in **residuals** and source catalogs located in **sources**.

`OasisPy.simulation.`**`SIM`**`()`

Master simulation function. Allows users to choose simulation type and supply all other simulation parameters.

OasisPy.test.**TEST**()

Tests the installation of **OasisPy** by downloading a set of images from an online public archive, adding fake sources to one of the images, and running the dataset through the **OASIS Pipeline**. If the fake sources are recovered, the test is a success. The images used are 118 second exposures of exoplanet HAT-P-37b taken with telescopes at the Las Cumbres Observatory. Results of the test are compared to control results located in **OasisPy**'s source code directory.

Returns Prints either 'TEST SUCCESSFUL!' or 'Test failure: Results do not match controls'.

OasisPy.montage.**MOSAIC**()

Interfaces with MontagePy to build a mosaic from a set of input images. All parameters are supplied through terminal prompts. See documentation for details.

OASIS is a toolkit for detecting variable objects in astronomical images by means of difference imaging. Includes the **OASIS Pipeline**, an all-in-one difference imaging utility that takes a set of input images and performs all necessary difference imaging steps on them, outputting a set of source catalogs upon completion. Difference imaging is a notoriously cumbersome task, especially for widely varying data. The **OASIS Pipeline** was built as a way to largely automate many of the menial processing steps involved in a difference imaging project.

The code is designed to perform quality difference imaging on data that vary widely in pointing, background, seeing, etc. Originally used in processing images of large galaxies, **OASIS** should work well for both extended objects and simple star fields.

It was developed for use in UC Santa Barbara's Optical SETI program (project homepage), but can be deployed in any application involving anomaly detection in astronomical data.

The OasisPy package is a set of Python modules that facilitate access to **OASIS**'s main functionalities.

CHAPTER 7

Features

- **Masking** – Masks cosmic rays, hot pixels, saturated stars, CCD defects, etc. Supports the use of weight maps often used in AstrOmatic programs.
- **PSF Modeling** – Computes PSF models of all input images using the AstrOmatic software `PSFex`.
- **Quality Control** – Ignores images below a user-defined *S/N* threshold and/or above a seeing threshold.
- **Registration** – Registers images to a chosen reference frame to subpixel precision.
- **Photometric Alignment** – Linearly rescales each image's intensity scale to match that of the reference image.
- **Stacking** – Performs a weighted coaddition of the input images to construct a deep, high *S/N* template image for use in the image subtraction step.
- **Background Matching** – Matches the background of the input images to the template image, using an image subtraction method that works well for extended objects with complicated backgrounds.
- **Image Subtraction** – Computes a PSF-matching convolution kernel to convolve with the template image, then subtracts the template from the input image. Uses the Optimal Image Subtraction (OIS) algorithm from Christophe Alard (paper).
- **Parameter Optimization** – Iterates over a range of OIS parameter configurations looking for the one that yields the best residual image. If a residual fails to meet a certain quality threshold for all parameter configurations, it is masked. Allows for a more robust subtraction that guarantees all residuals in the dataset will be of optimal quality.
- **Source Extraction** – Uses the AstrOmatic program `SExtractor` to extract variable objects from residual frames.
- **Source Filtering** – Filters out subtraction artifacts and other phony variable sources.

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