Point-spread function modeling for the James Webb Space Telescope

Colin Cox and Philip Hodge
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, Maryland 21218

ABSTRACT

We describe software which models the Point Spread Function of the James Webb Space Telescope. The software is designed to be expandable to incorporate optical and instrument data as they become available. An initial model of the detector used in the Near Infra-red Camera has been used to generate realistic stellar images.

Keywords: Optical Modeling, Telescope, PSF

1. INTRODUCTION

We have written software to model the Point Spread Function (PSF) of the James Webb Space Telescope. The software is written using the Python programming language and makes use of freely available compilers and software. The complete software package is freely available for general modeling use. All inputs and outputs are in standard FITS formats or in easily created text files. The design is table driven, with the idea that model inputs describing the pupil function, wavefront aberrations and filter functions may be used initially but will be replaced as more information and measurements become available. We include here an initial model of detector effects including readout noise and charge diffusion.

2. METHOD

2.1 The first step

Pupil files describing the extent of the pupil plane are FITS images containing zeros to indicate where no light is transmitted. The transmission areas will normally contain the value 1.0, although reduced transmission or edge effects might be expressed by using values less than 1.0. Aberrations are described by Optical Path Difference (OPD) files, which describe the difference between an ideal incoming spherical wavefront and that produced by an actual or modeled optical system in the form of displacements at each point on the wave front. These files are also given as FITS images and contain displacements measured in nanometers. These images will be matched to the pupil image in the sense that only phases in pixels corresponding to non-zero pupil values will be meaningful. There will be several OPD files describing different optical components to be combined in the program. Initially we use realistic model OPDs designed to express the type and degree of aberrations we expect to deal with.

Source spectra are taken from HST's library of Kurucz stellar atmospheres[1] which contains spectra for a wide range of metallicities, effective temperatures and gravities. For this simulation the software restricts itself to a representative subset representing 39 stellar types. The spectra are in the form of FITS tables, the data columns being wavelength and flux. The units of each are given in the header and are normally Angstroms or microns for the wavelength and ergs/s/cm^2/Å for the flux normalized to a given magnitude star. FITS tables are also used to describe the filter throughput and consist of columns of wavelength and fractional throughput values. These may be synthetic or taken from measured filter throughputs. Selection by stellar type will extract one of the 39 representative files. A moderate number of filters are included with the calculation software.

2.2 Computation

The Fraunhofer approximation to the Kirchhoff's diffraction integral describing the image formed by a converging monochromatic wave of wavelength λ is $\psi = \int_S e^{-ikr} dS$ integrated over the wavefront where k = 2π/λ and r is the distance from a point on the wavefront to the image position. The variations in r are expressed by optical path differences d (x,y) and the overall distance adds only a constant value to the phase. The extent and amplitude of the wavefront is described by the pupil image and the calculation reduces to $\psi(u,v) = \iint e^{-\frac{2\pi i(ux+vy)}{\lambda}} A(x,y)dxdy$ which is recognizable as a two-dimensional Fourier transform. The fundamental calculation is then to take the pupil image P, and the sum of the phases ϕ and form the complex pupil function $A = Pe^{i\phi}$ The phase ϕ depends on the wavelength λ being modeled and is then simply the optical path difference multiplied by $2\pi/\lambda$. The Fraunhofer diffraction amplitude at the focus is given by ψ, the Fourier transform of this image and then the PSF by the power $|\psi|^2$. This is done for wavelengths common to the ranges in the spectrum and filter throughput files and the sum formed, weighted by the integrated product of spectral intensity and throughput. To interpret these calculations in physical terms we need to specify the pixel scale and image size of the initial pupil and phase images. We choose a pupil array that is larger than the actual aperture diameter D by a factor F, typically of value 4, and filled with zeros outside the physical pupil size. The angular size of the pixels in the PSF image is then $\frac{1}{F}\frac{\lambda}{D}$. For our 6.5m aperture, a wavelength λ of 1µm and factor of 4 we would have a pixel of angular extent 3.84 x 10^{-8} radians or 7.9 milli-arcseconds. For an f-number of 1/16.67 l (a focal length of 108m) the linear size is 4.2µm. Since this size varies with wavelength the arrays are resampled onto a chosen pixel size to form the broadband PSFs.

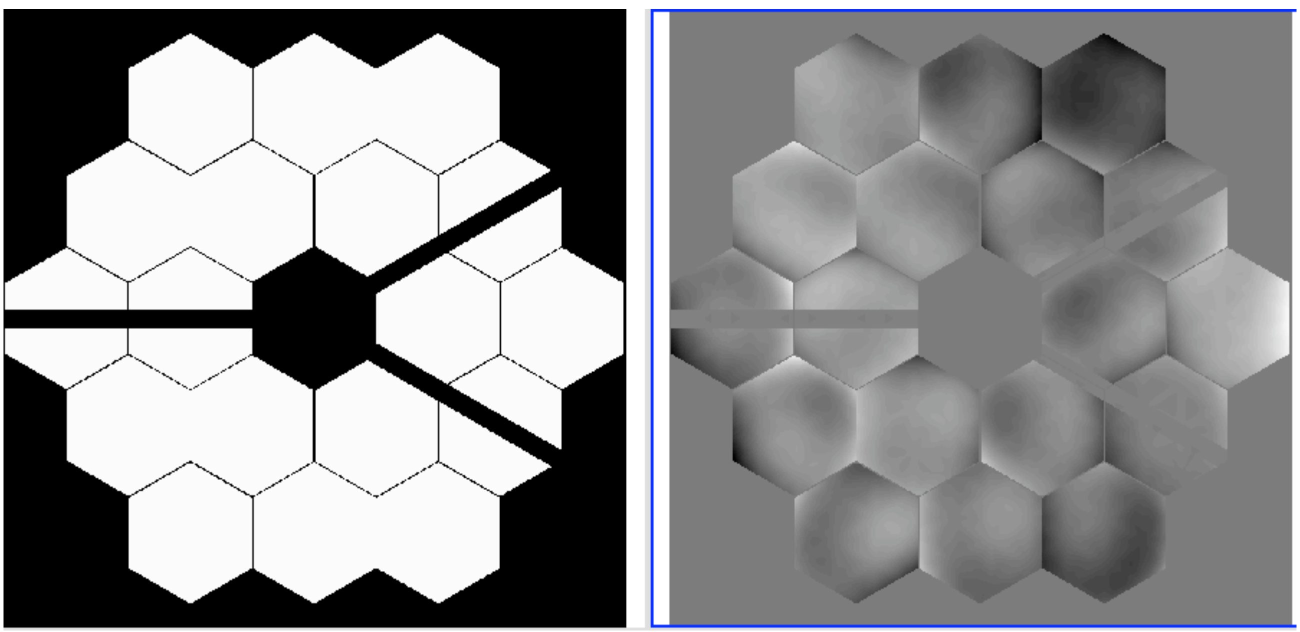

Figure 1: Illustration of the pupil image and Optical Path Difference files, being the amplitude and phase of the complex pupil image supplied to the software. The eighteen hexagonal mirrors are shown and the three secondary mirror supports. In the pupil image zero is represented by black, while in the OPD image zero is mid-grey.

2.3 Integration over bandpass

The weights to be applied to each wavelength are calculated as a product of the source spectrum and the filter throughput. Source spectra are extracted from the Kurucz models supplied in the HST library. The particular spectra are selected by stellar type. A subset of these spectra is supplied as part of the program package. Source spectra are given in units of ergs cm^{-2} s^{-1} A^{-1}. For use in the PSF modeling we need photons/sec and so the spectra are multiplied by the wavelength. The absolute flux is not considered for the generation of PSF shapes; each image is self-normalized to give unity total flux.

Filter throughputs have been generated as top hat shapes based on nominal filters proposed for NIRCam (the Near Infra-red Camera to be installed on JWST). Other real or synthetic filter shapes may be used by supplying FITS tables of wavelength and throughput. Given a filter profile we divide it up into a number of equal width wavelength bands straddling the range for which the throughput is more than 1%. For each band we form the integrated product of filter throughput and spectral intensity to give a weighting factor for the wavelength at the center of each segment. The number of segments is user selectable. A value of five to ten, depending on the bandwidth gives results that are not noticeably changed by using larger numbers.

2.4 User Interface

The calculation will generate PSFs for any object spectrum and filter bandpass. In principle it could work for any optical system for which pupil and wavefront details are known, but here we restrict ourselves to discussion of the JWST model. The object spectrum will normally be chosen by selecting from a list of spectral types, although supplying any spectrum is supported. Similarly, the filter function is most easily selected from a supplied set of filter names, but the user may supply a FITS table containing wavelengths and throughputs if desired. Alternatively a bandpass may be specified by supplying upper and lower limits plus the number of intervals within the band. This allows for the possibility of a monochromatic case. A plot overlaying the spectrum and filter bandpass is shown. At this stage all choices may be revisited if necessary.

Subsequently, the pupil and OPD files have to be chosen plus a name for the file to contain the output. The default forms are as illustrated in Figure 1 and are designed to represent the JWST hexagonal mirror structure with its three secondary mirror supports and a degree of low frequency aberrations which give a Strehl ratio of about 0.8. The two images illustrate the amplitude and phase of the complex pupil image. All these specifications can be edited before giving the command to begin the main calculation which takes several minutes to run.

2.5 Presentation of results

The outputs are given as sub-sections of the image that encompass a reasonable area centered on the PSF. We have chosen a 512 by 512 image. Header keywords indicate the pupil and optical path difference files used, the oversampling factor, the aperture diameter, the wavelengths used and the calculated weighting factors. The output pixel size is given in degrees. Although it might be more natural to supply this in arcseconds we are following a FITS convention. With an oversampling factor of 4 this value will be ¼ the selected pixel size Additionally, radial intensity plots and profiles in x and y directions are shown.

3. SOFTWARE EXTENSION

3.1 Detector effects

We have recently extended the software to model some effects expected in making real observations. We sample the image to the actual size of NIRCam pixels and include dark current, readout noise and charge diffusion. The pixel size is 0.032 arcsec. Dark noise has been taken to be 0.01 counts.sec^{-1}.pixel^{-1} and the total readout noise is required to be less than 9 electrons. Such calculations can provide estimates of the limiting observable magnitude for a given exposure time and support realistic simulations for planning observations. A stellar magnitude of 24 and a 1000 second exposure time have been chosen, somewhat arbitrarily for illustration purposes but the noise rates etc. are derived from laboratory measurements[2] on a detector of the HgCdTe type to be installed in NIRCam

4. RESULTS

4.1 Images

A few results of running the program are presented here. First an ideal PSF at 2 microns is compared with an aberrated version. Using an OPD file containing all zeros generates the ideal PSF. The peak intensity of any PSF image divided by that of the ideal PSF gives the Strehl ratio, a measure of the quality of the optical system. A requirement for JWST is that the Strehl ratio should be better than 0.8 at a wavelength of 2 microns. Subsequently we show as images and profiles the effect of adding readout noise and charge diffusion to the output, although the latter condition, even with an extreme value of 1.5% diffusion shows no visible effect even in the profiles.

To obtain a copy of this PSF modeling program, please contact either of the authors cox@stsci.edu or hodge@stsci.edu

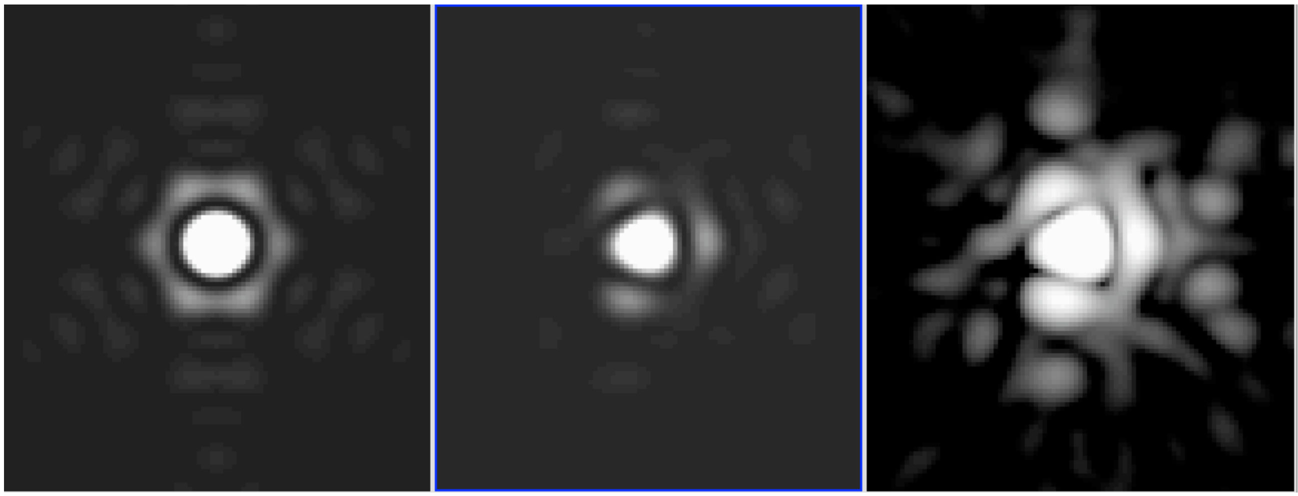

Figure 2: Three point spread functions generated by the program. First an unaberrated monochromatic PSF at 2 μm, second the monochromatic PSF with some degree of aberration and thirdly a PSF corresponding to a 0.5 μm bandwidth centered at 2 μm.

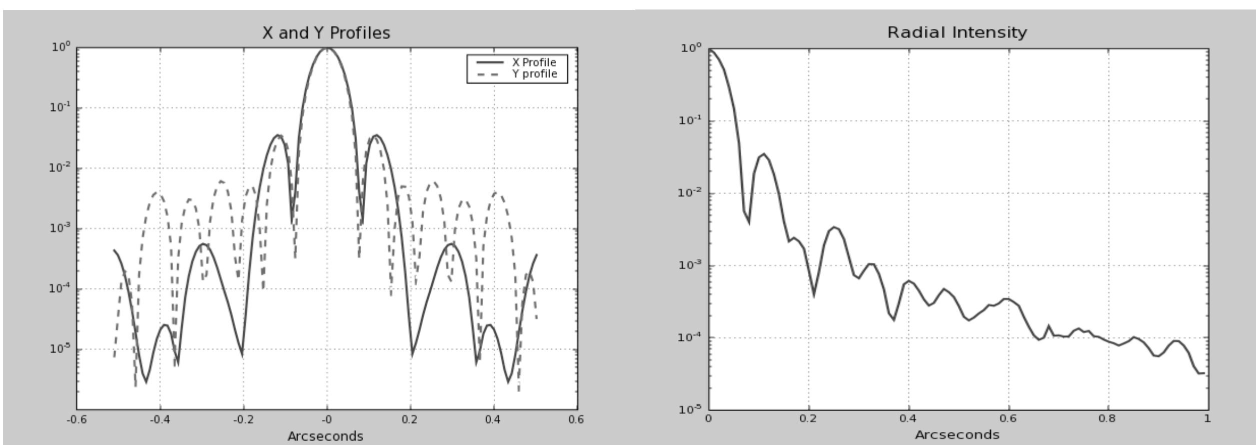

Figure 3: Profiles and radial intensity plot for an unaberrated point spread function at 2μm wavelength.

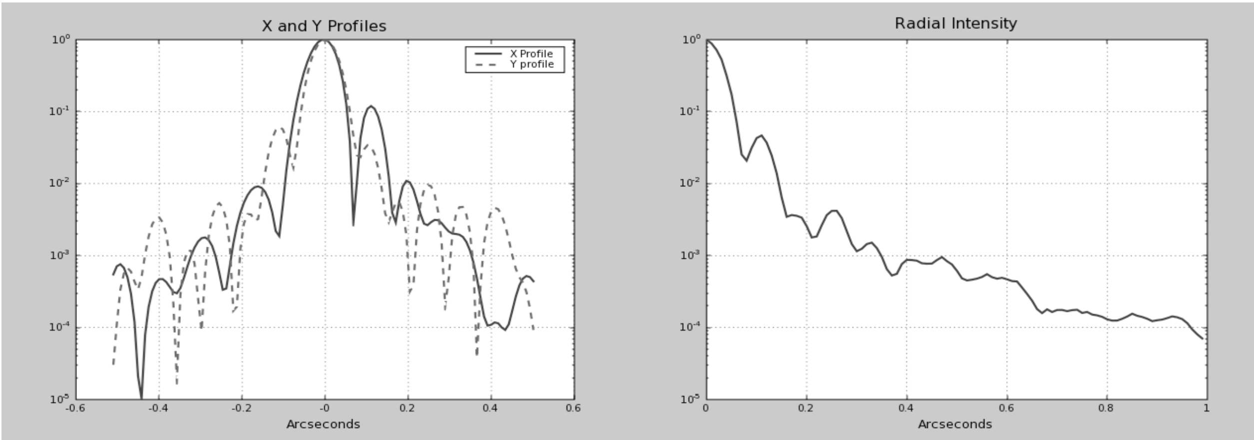

Figure 4: Profiles and radial intensity for a realistically aberrated monochromatic point spread function. The Strehl ratio is 0.81 and so the peak intensity of the profile graph is 0.81 times that in the previous plot.

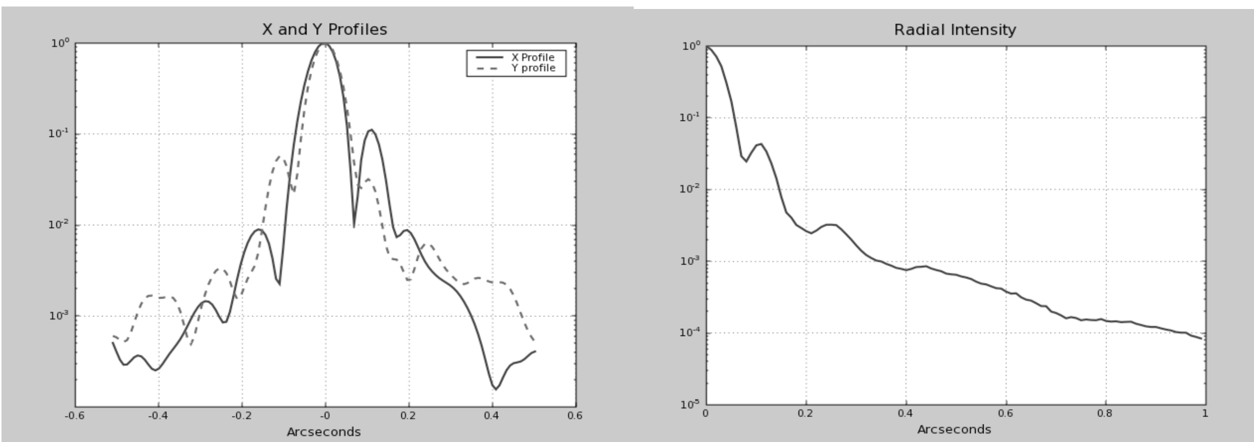

Figure 5: Profiles for a wide band PSF. The wavelength range is from 1.75 μm to 2.25 μm. The features in both diagrams are smoothed compared with the monochromatic images.

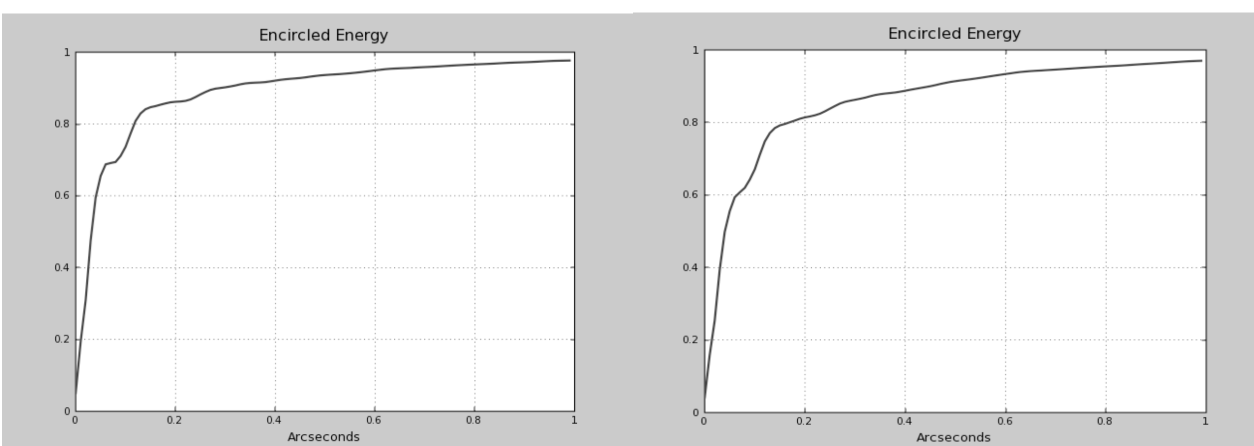

Figure 6: Encircled energy plots for the ideal (left) and aberrated (right) PSFs. For the ideal spot, 80% of the energy falls within a 0.12 arcsecond radius, whereas for the realistic spot, 80% falls within 0.17 arcseconds.

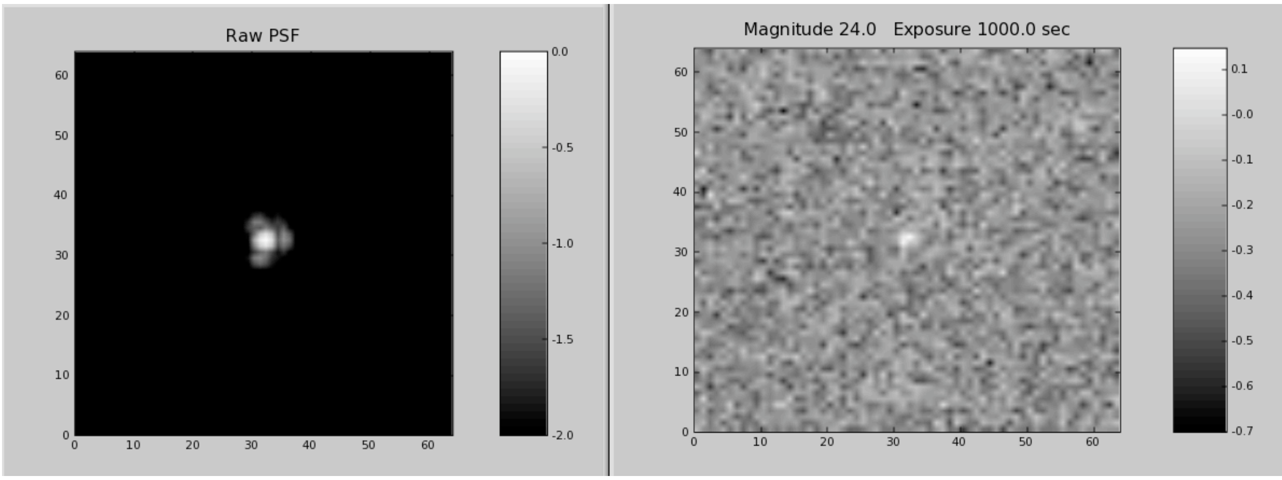

Figure 7: An ideal image compared with a model of a 24th magnitude star exposed for 1000 seconds including readout noise and charge diffusion effects. The intensity calibration bars give the log base10 of the intensity. Both images are normalized to the peak intensity in the Raw PSF.

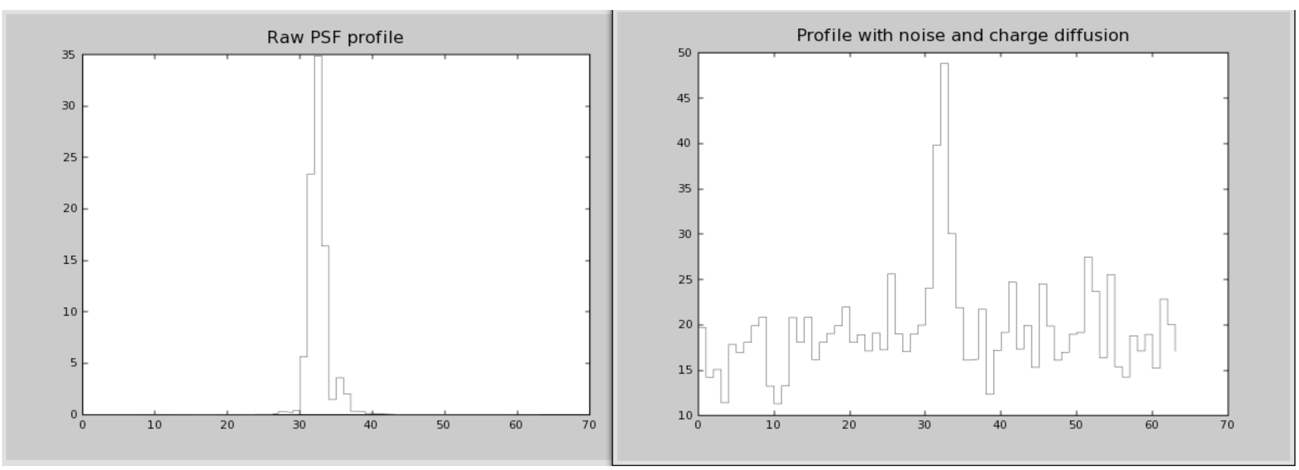

Figure 8: Profile plots corresponding to the images in Figure 7.

5. ACKNOWLEGEMENTS

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6. REFERENCES

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