Interim report on the status of 2D PSF modelling

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Abstract

We present interim conclusion of our work which aims to model PSF in PFS project. The main goal of the current stage is to accurately model PSF in the data taken at optical bench at LAM. Especially crucial is modelling of the PSF wings, in order to eventually accurately subtract the contribution of skylines from the scientific data. We show that the data taken in focus at LAM exhibits much stronger PSF wings than what would be expected from creating optical PSF (either from Zemax or our internal model) and convolving it with reasonable model for fiber and CCD charge diffusion.

1 Overview

I have been working on this project since September 2017 with the goal to accurately model 2D PSF of a PFS spectrograph. Although we have spent a lot of time and effort in examining many effects and adding complexity to the model we have not been able to accurately describe and predict PSF from the data taken at the optical bench at LAM.

Very briefly, current algorithm models wavefront as a combination of Zernike coefficients and allows for the exit pupil to be non-uniformly illuminated. Created optical PSF is convolved with tophat to simulate fiber effects and with additional Gaussian to simulate CCD charge diffusion effect. Result is then downsampled to the resolution of the data and compared with the actual data.

Here I will present evidence that there is additional flux in the wings of the PSF of the focused data which is too great to be reasonably described by the our model and/or Zemax. I believe that this is probably due to some form of scattered light, but this discussion is beyond the scope of this report in which I describe my reasoning for my statement above.

In Section 2.1 we summarize how the data was collected and reduced. In Section 2.2 we summarize how the optical PSF was created from Zemax. We use Zemax instead of our model to eliminate possible source of errors. In section 2.3 we compare results from these two approaches and show that power in the wings of PSF is only comparable in the case of unrealisticly small numerical aperture (NA) in Zemax. In Section 3 we discuss, in light of these findings, why our efforts up to this point were unsuccessful. In last part, Appendix A, we show that our conclusions about excess scattered light are not due to poor background subtraction.

2 Flux in the wings

2.1 Data

Data presented here was taken on December 15, 2017 and is part of the sequence which took images of HgAr lamp through different position of defocus. Data was dithered when in focus by half of pixel to produce 2x oversampled images. Exposure time was 5 seconds at each of these dithered positions and 3 realizations of each image were taken to increase signal to noise ratio. I have created images that I am presenting here from runs 8588-8590, 8591-8593, 8597-8599 and 8600-8602. As data is 2x oversampled, each pixel in the images that follow has a physical length of 7.5 μm. In this report I am showing results from fitting PFS at the centre of detector as this is a region where we expect the smallest amount of optical aberrations.

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Data show some contamination in the wavelength direction which we believe is due to contribution of continuum in the lamps. I have estimated magnitude of this contamination by measuring flux in regions 100 pixels from the centre of the PSF and subtracting from the data (We plan to subtract this contribution in the future as a part of the pipeline - for this dataset this was not implemented yet as no corresponding fiber traces were taken). I show that the data is "well-behaved" in Appendix A.

2.2 Zemax

The base for modelling is Design-C3-v14 model which is available on Sumire. This Zemax model does not contain detector box and struts. I have therefore added a simple description of detector box and struts. Detector box is modelled as two rectangular obscuration with width of 96 mm and depth of 62.5 mm, as specified in the literature and by Jim. Struts are modelled as "spider" obscuration at the position of the detector, with each arm 12 mm wide. Note that the "depth" of spider arm is not considered and that I determined the width of the arm empirically from the defocused data. There is definitely room for improvement here.

We have simulated optical PSF using the FFT PSF tool which produces images which are at least 100x oversampled (depending on the input NA used). We have then convolved this optical PSF images with the tophat which creates PSF with FWHM of 55 μm, which is the FWHM expected from both Jim's simulation and Zemax modelling for the input fiber of 128 μm. We have also convolved the data with Gaussian with $\sigma = 7\mu m$ which is charge diffusion σ expected for photons at around 800 nm (reference - Jim), which is wavelength probed in the center of the detector. We have then downsampled these images to match physical scale of the data while ensuring that centres of the flux for simulated images and the data are the same.

When creating figures for visual inspection we have also added artificial noise generated using values from variance images. Typical variance for these images in the regions without signal is around 60 (3 images with variance of around 20). Note that we have not modelled the slit and slit holder in Zemax which will also contribute to diffraction effects. Given that they occupy smaller area than spider we expect their contribution to be sub-dominant. We have verified that results from using FFT tool and Huygens tool in Zemax are comparable.

2.3 Comparison of PSF wings in Zemax and in the real data

We summarize our findings in Figures 1 and 2.

Lets first look at Figure 1. The plot shows the flux in a single pixel as a function of the distance from the centre of the image. This is done by averages flux from all pixels at this radius, so this plots "erases" angular information. Note the logarithmic scale on y-axis.

The data is shown in blue. We can clearly the area dominated by the top hat function of the fiber and recognize FWHM of around 27 μm. Soft pink lines shows square root of a mean variance of single pixel and is indicated to give some feeling about scale of errors in the model. Note that, because flux is calculated from many pixels, actual errors on measurement are lower than indicated with pink line. Two images of the data from the central part of the detector, from two different fibers are shown in bottom line of Figure 2. Results from these two spots are very similar so we shown only one line in Figure 1 to improve clarity.

With red line we show results of simulation "without obscuration", i.e., without detector box and spider. Not surprisingly, the result is almost pure spot, given that optical PSF is small (Airy disk radius is ~ 1 μm). With yellow line we show result after adding we show result after adding obscuring elements (detector and spider, implemented in Zemax as described above). We see that, even though there is more flux on the larger scales, this is not even remotely enough to explain the data. Results from these simulation are shown in the top row of Figure 2.

I believe this is concisely explains the reason why the efforts undertaken so far were not successful in modelling the data and predicting the PSF in the focus. Our models from defocused data describe reasonably well the illumination and the size of various obscuring elements in the exit pupil of the camera. When these same values get "translated" to focus they do not have enough power to generate strong wings in the data, as evidenced in Figures 1 and 2. We elaborate some more in Section 3 and below.

We will now explore what kind of illumination would produce such strong wings in the focused data and is that illumination consistent with what we see from defocused data. We see that in order to explain the flux on large distances from the centre of the spot (> 75 μ m) when using

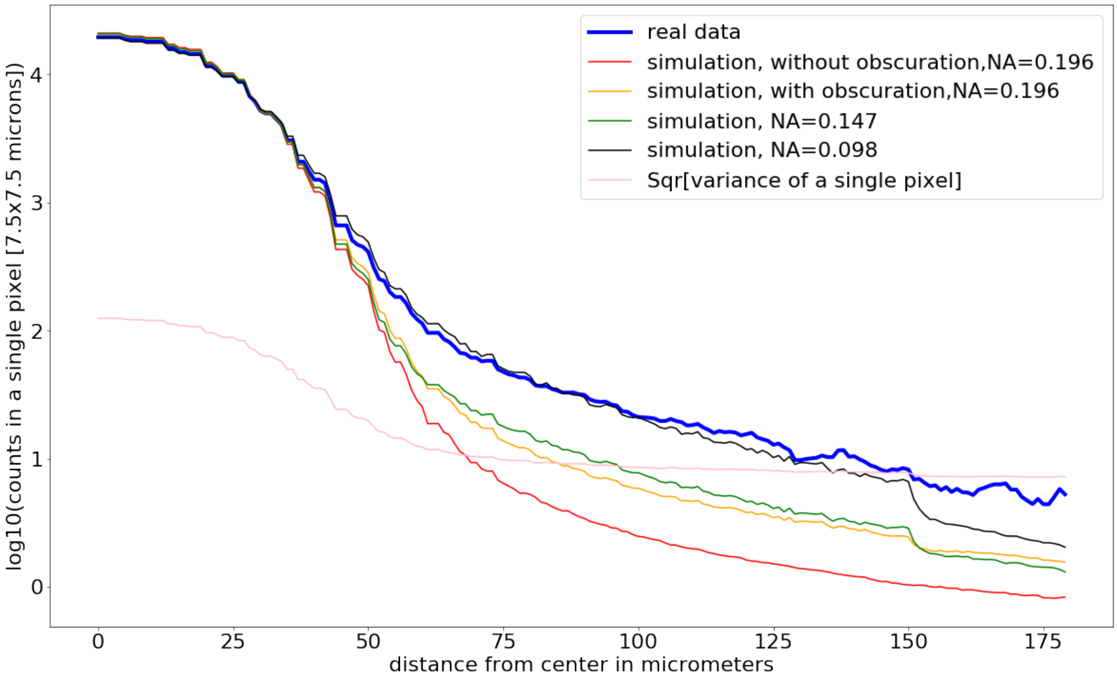

Figure 1: Logarithm of the mean flux in one 7.5 μm wide pixel as a function of distance from the center of an image. Blue thick line shows data. Red line shows results of Zemax simulation without any obscuring elements, while yellow line shows result after adding detector box and struts in the model. Green and black line shows results after we have reduced object NA from default value of 0.196 to 0.147 and 0.098. Faint pink line shows square root of mean variance for pixels at a given distance. Note how realistic model with NA which we expect (yellow line) under-predicts wings of the PSF. See also text (Section 2.3).

pure optical model we have to decrease effective aperture of the system and therefore increase the importance of diffraction effects. We show in Figure 1 results for two systems, in which we decreased the object numerical aperture. In green we show result after lowering NA from default value of 0.196 to 0.147, and in black we show results with NA=0.098. As expected we see that there is more flux in the wings of the PSF. Images are shown in the middle row of Figure 2.

We see the drop at 150 μm in the simulated data which is due to the fact that images are 150 μm wide and at 150μm simulated images lose contribution from strong "cross feature" present in simulation. The real data shows excess in the diagonal regions of the image. Given how crudely we simulated struts this is perhaps not alarming.

Even though image with severely limited NA (NA=0.098) has enough flux to fully account for wings of the PSF as seen in the data we do not believe that this is reason for this amount of flux in the wings of the PSF seen in the data, due to discrepancies in the defocused data. In Figure 3 we show expected result for defocused data. Left panel is done with default NA=0.196 and right panel with NA=0.098. Compare this with Figure 4 showing defocused data and it is obvious that NA=0.098 simulation can not describe defocused data.

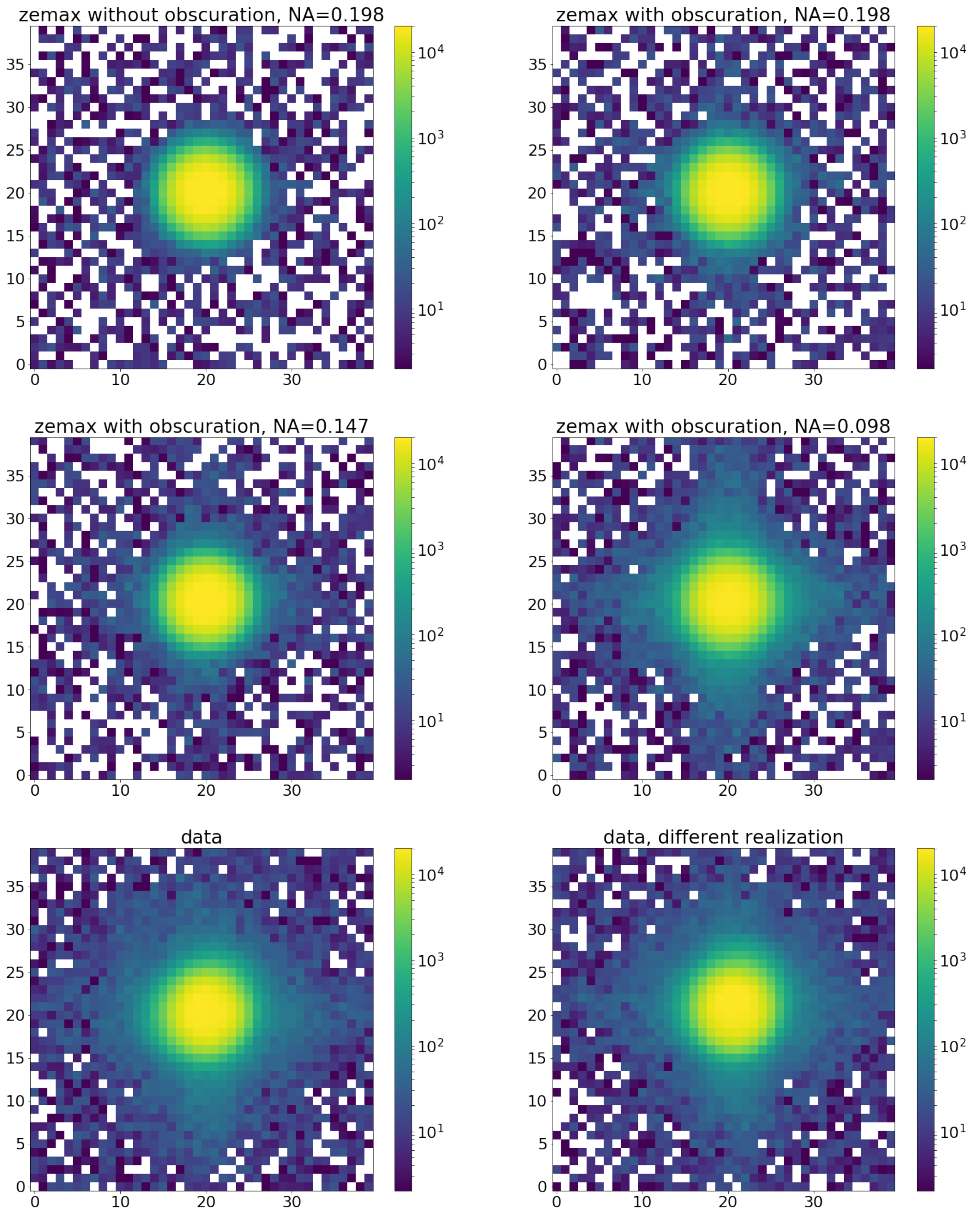

Figure 2: Figure showing expected PSF given different assumptions about the illumination of the camera in top and middle row, and the data in the bottom row. See text for details.

3 Effects on the fits and why our efforts so far have been unsuccessful

As we have hinted before, we can now also understand why our "predictions" from defocused data were not successful in predicting focused data. As we have seen in the discussion above, the defocused data prefers to have large numerical apertures, while in order to explain focused data we need very small numerical apertures. This is exactly what was seen in our fits, as shown in Figure 5. More defocused data generally has larger exit pupil (i.e., larger numerical aperture), while fits to focused data need smaller exit pupil (i.e., smaller numerical aperture). We wish to point here

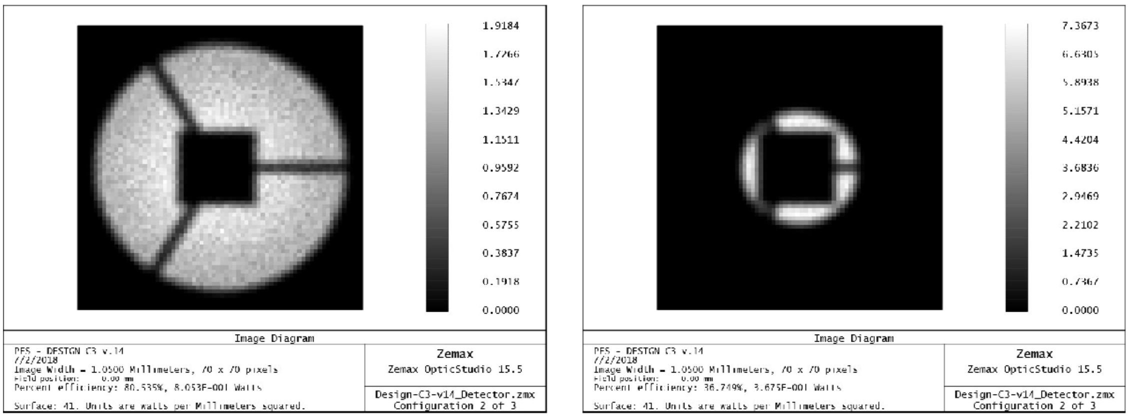

Figure 3: **Top left**: defocused Zemax model at NA=0.196 ;**Top right**: defocused Zemax model at NA=0.098. Compare with Figure 4.

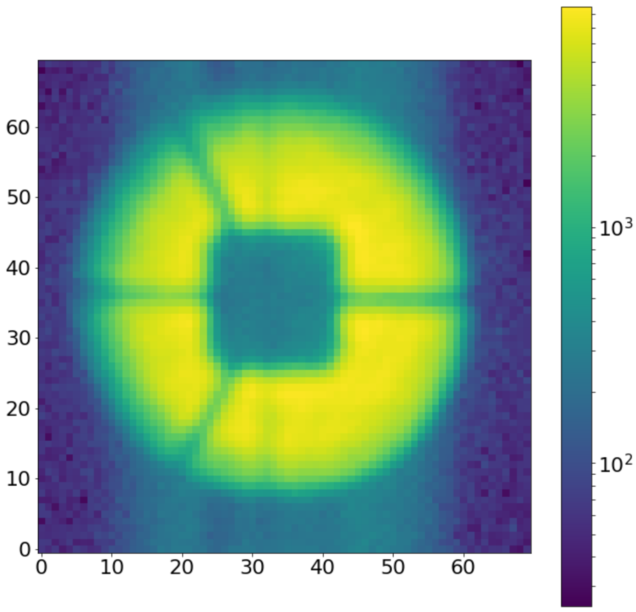

Figure 4: Example of the real defocused data. Compare with Figure 3. Even though NA=0.098 creates enough flux to roughly explain wings of the PSF in the focused data, it is not consistent with the defocused data.

that the quantity shown is not the only one describing the illumination of the pupil in our fits, so it is not surprising that results are not completely consistent on both sides of the focus. The full line on Figure 5 shows result of the fit in which we fit all the data at once which is dominated by the defocused data and therefore resulting effective numerical aperature is relatively large. In Figure 6 we show results of our prediction in the focus compared to the data. As we can see, the fit is not successful as it severely under-predicts the flux in the wings of the PSF in the data. As we elaborated above this is not surprising as we believe now that the wings are dominated by scattered light which is not due to optical PSF.

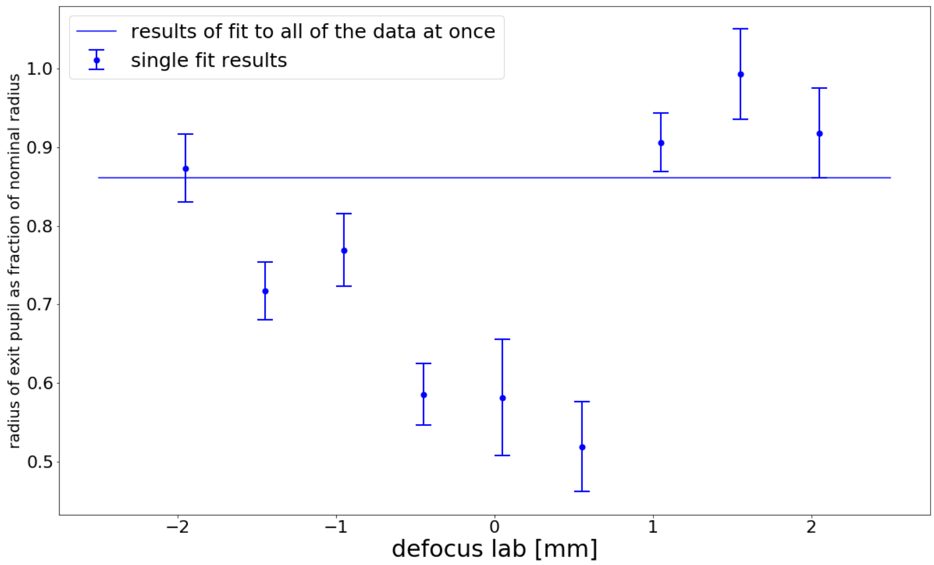

Figure 5: Size of the exit pupil, as a fraction of the expected exit pupil size from Zemax. Data point show fits to single images, while full line shows fit to all of the data at once. This quantity corresponds quite closely to the numerical aperture quantity that we varied in the Zemax modelling. We see that data closer to the focus prefer smaller exit pupil (equivalent to smaller NA) as the model tries to get more flux in the wings of the PSF. That is inconsistent with defocused data which tend to prefer numerical aperture which are closer to what we expect from Zemax modelling.

A Wide view around single spot

Below, in Figure 7 we are showing larger view around the spot which we analysed. This is just to reassure the reader that the additional flux that we have claimed exists in the wings of the PSF is not due to poor or wrong background subtraction. We have also verified that the average flux falls to 0 (becomes consistent with pure noise at around 200 μm) when we apply the same procedure to wide view of the data as the procedure used to create Figure 1.

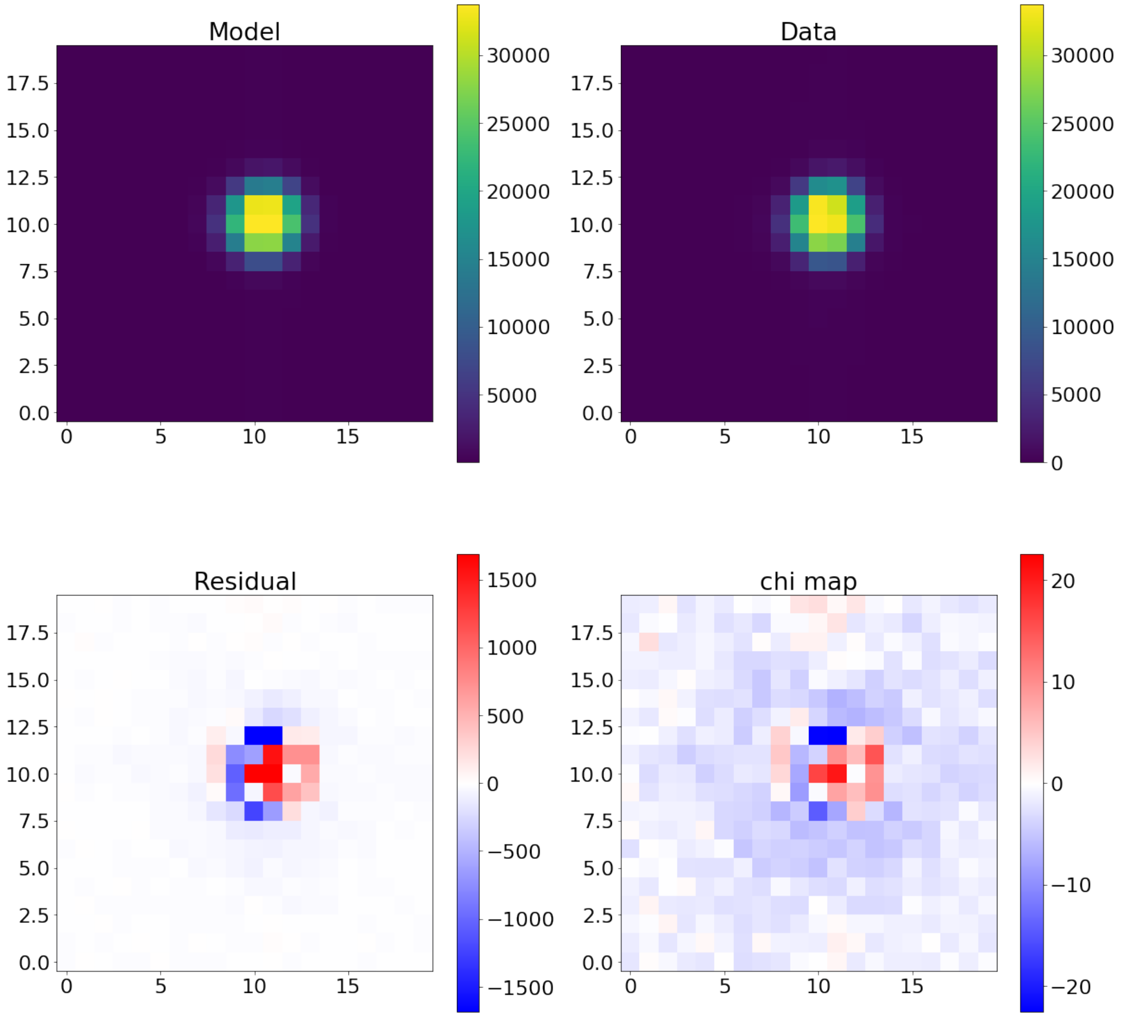

Figure 6: Example of typical result from fitting the defocused data and trying to predict data in the focus. **Top left**: our model, **Top right**: Data, **Bottom left**: Residual, **Bottom right**: we minimize χ^2, where χ=(data-model)/$\sqrt{\text{variance}}$. This panel show pure χ so that we can see sign of the discrepancy. Our model underestimates flux in the wings PSF, as expected given the discussion in Section 2.3. Small excess on the central top and bottom parts of the chi map is a result of the old code in which continuum contribution was overestimated, as the continuum contribution was not removed before the analysis, but left as a free parameter in the fits.

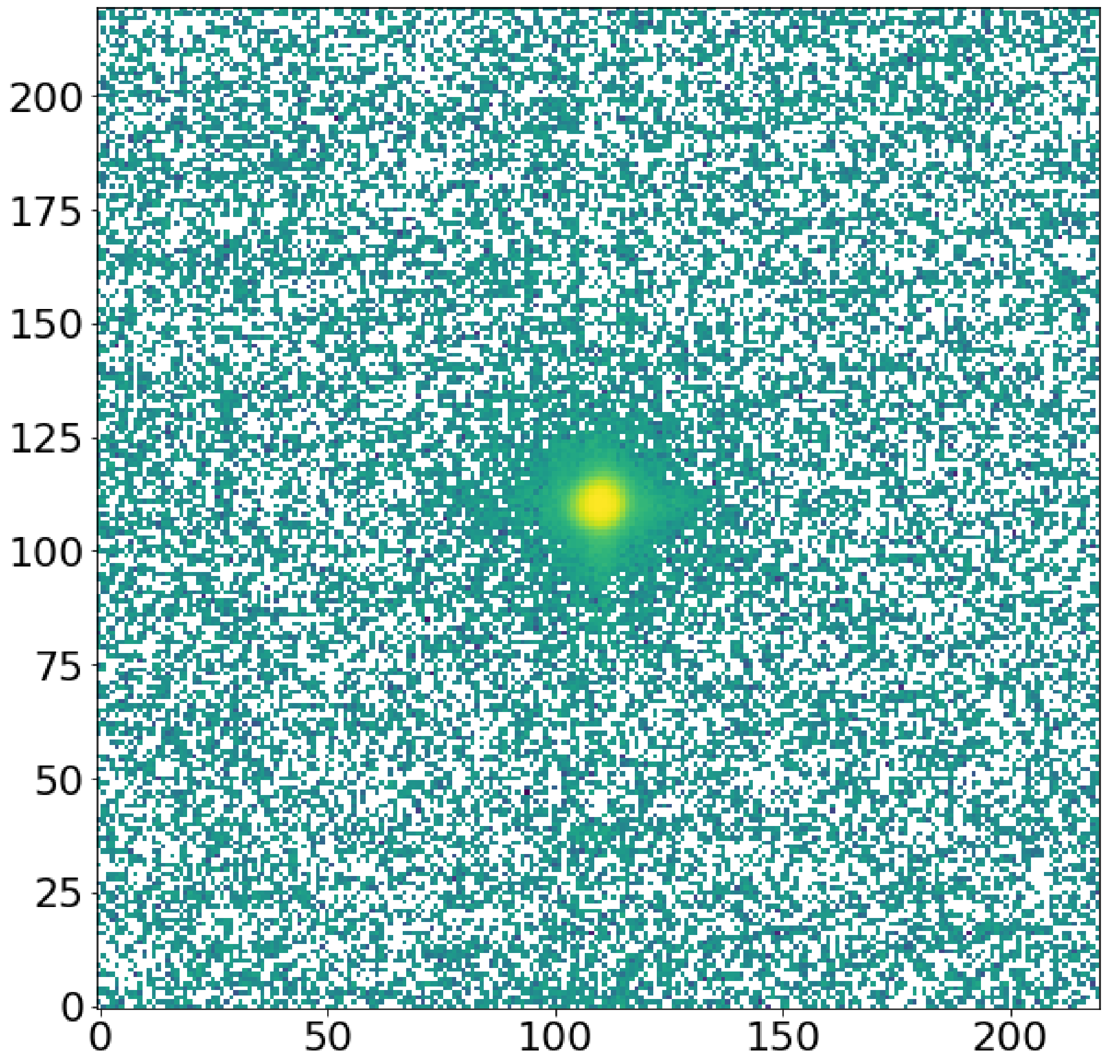

Figure 7: Larger view around one of the spots in the data that we have analysed. The extra flux around the PSF is not due to poor subtraction of the background.