A CLASSIC THESIS STYLE

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An Homage to The Elements of Typographic Style

September 2015 – version 4.2

ABSTRACT

Short summary of the contents... a great guide by Kent Beck how to write good abstracts can be found here:

https://plg.uwaterloo.ca/~migod/research/beckOOPSLA.html

We have seen that computer programming is an art,
because it applies accumulated knowledge to the world,
because it requires skill and ingenuity, and especially
because it produces objects of beauty.

— knuth:1974 [knuth:1974]

ACKNOWLEDGEMENTS

Put your acknowledgements here.

Many thanks to everybody who already sent me a postcard!

Regarding the typography and other help, many thanks go to Marco Kuhlmann, Philipp Lehman, Lothar Schlesier, Jim Young, Lorenzo Pantieri and Enrico Gregorio[1], Jörg Sommer, Joachim Köstler, Daniel Gottschlag, Denis Aydin, Paride Legovini, Steffen Prochnow, Nicolas Repp, Hinrich Harms, Roland Winkler, and the whole LaTeX-community for support, ideas and some great software.

Regarding LyX: The LyX port was initially done by *Nicholas Mariette* in March 2009 and continued by *Ivo Pletikosić* in 2011. Thank you very much for your work and the contributions to the original style.

1 Members of GuIT (Gruppo Italiano Utilizzatori di TeX e LaTeX)

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LISTINGS

ACRONYMS

DRY Don't Repeat Yourself

API Application Programming Interface

UML Unified Modeling Language

1 INTRODUCTION

A major and succesful topic in astronomy has been the discovery and characterization of exoplanets. This intrest has sparked great progress in the field of high contrast imaging resulting in new imaging techniques and instuments. Though as of writing 3,949 planets [**nasa**] have been confirmed little is known about theire formation. Certain is that a so called protoplanatary disk is an importand stage in the formation of a planatary system. The disks can be observed best within the visable spectrum and infrared though ALMA has also had succes in observing disks in the radio spectrum.

It is however a great challenge to aquire observations of such a disk due to the high contrast with its star and the required angular resolution. ****explain why light from a star (dot) can hide planatary details in a normal telescope (is it only sys+atmosph psf for appamture?)****. To observe with sufficient resolution adaptive optics are used. This negates most of the atmospheric seeing.

Reducing contrast is done with coronagraph, an instrument that blocks out the direct light from a star. The classic lyot coronograph (Figure 1) blocks direct star light using two focusses. In the first focus an opaque mask blocks placed where thes star is diffuses and absorps the direct star light. Then between the focusses a ring shaped mask blocks most of the now diffused star light. Then at the second focus the image is made as usual.

However a classical coronograph is not sufficient for observing disks. The vector Apodizing Phase Plate (vApp) [**papervApp**] is a different type of coronograph placed at the pupil of a telescope. The vApp blocks starlight by modifing the phase of incoming light. This phase change flips the light in a D-shaped region around the star to the other side. Any faint object next to the star in the now dark re-

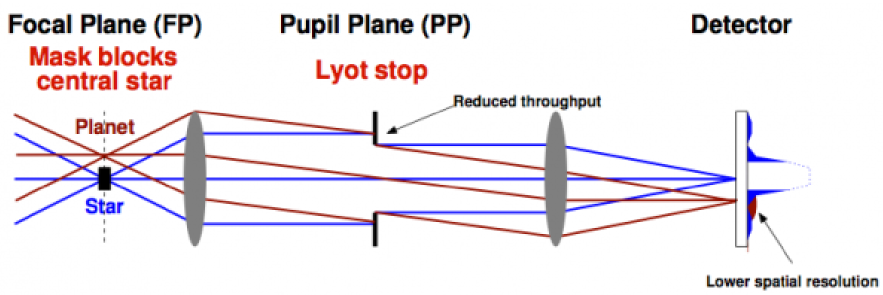
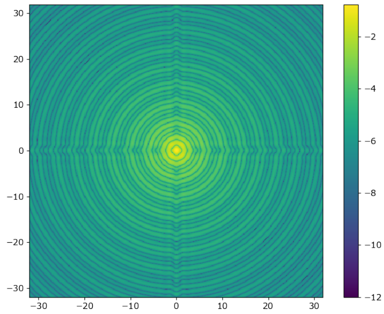
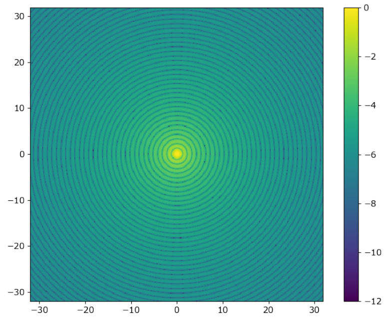


Figure 1: optical layout of a loyt coronograph, by Matthew Kenworthy, from https://home.strw.leidenuniv.nl/ kenworthy/app

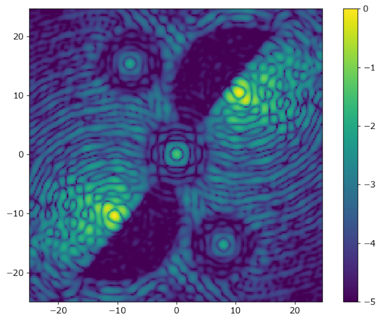
gion becomes detectable. Compared to the classic lyot coronograph the vApp reduces the starlight to a greater degree, see Figure 2.



(a) psf of a classical lyot coronograph



(b) psf of a telescope without coronograph



(c) psf of the vApp

Figure 2: The point spread function (psf) is the image an instument produces when looking at a point source such as a star. Here we sees the psf of a instument without a coronograph, with the classical lyot coronograph and a one using the vApp

The vApp has been developed to detect rocky planets in the habitable zone of stars. However it could also allow us to resolve disk features and study disks in greater detail directly. However as the vApp changes the entire image it is challaging to differentiate disk features from vApp artefacts.

Here we study what the effect is of both the vApp and reduction methods ADI and RDI on the apparent morphology of the disks. Here we try to characterise artificial disk observations with the vApp.

TODO overview thesis

https://en.wikipedia.org/wiki/Coronagraph

2 THEORY

Here we discuss what an psf is, how it helps us describe an optical system and how they natuarally apear from basic optics. Then we look at the different types of disks that have been observed and what contrasts we expect.

2.1 PSF

We can describe what happens to light going through an optical system with its point spread function (PSF). It describes the light intensity on the focal plane (where the sensor is located) as a function of x and y when a single light ray is imaged on the center of the focal plane.

We derive a way to find the PSF from the Hygens-Fresnel Principle. It states any part of a wave can be described as a front of inifinite point sources interfering with one another. An optical element can change these arrangement of theses sources, for example an aperture allows only a small area to be filled with these point sources as illustrated in Figure 3.

We find the electric field at a point P at distance R by summing up the fields of these infinite point sources taking into account the different distances to R. Writing the infinite sum as an integral we get Equation 1 for the electric field at a point P some distance R from an apperture.

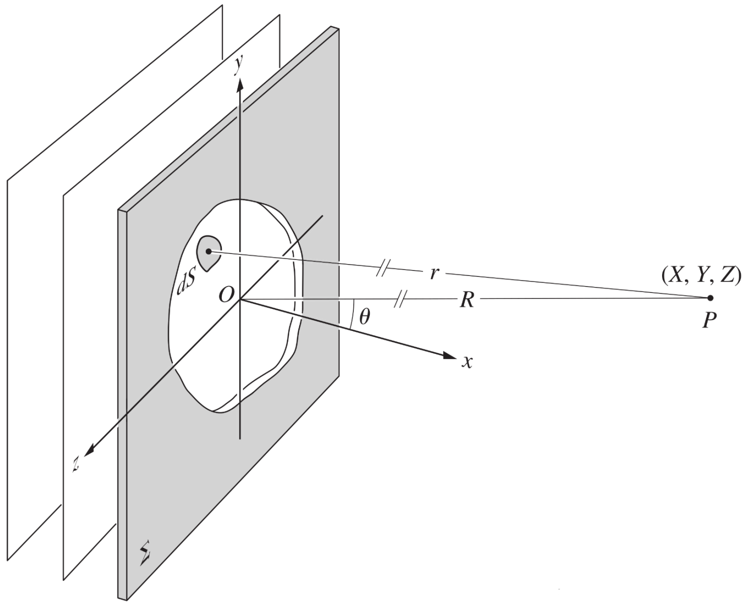
$$E = \frac{\varepsilon_A e^{i(wt-kR)}}{R} \iint_{Aperture} e^{ik(Yy+Zz)/R} dS \tag{1a}$$

Here capital Y, Z describe the position in the imaging plane in which P lies as seen in Figure 3. Small letters y and z are the position in the apperture plane. The integral is over the apperture, only integrating over the transparent parts.

To account for changes in phase and not only magnitude of the field caused by Optical instruments we including an aperture function instead of just integrating over the shape of the apperture. This results in:

$$\mathscr{A}(y,z) = \mathscr{A}_0(y,z)e^{i\phi(y,z)} \tag{2a}$$

Figure 3: Fraunhofer diffraction from an arbitary aperture, r and R large compared to the size of the hole. Extracted from Optics 5th edition, by [4]



Here the amplitude of the apperture function comes from $\mathscr{A}_0$ and the phase from $e^{i\phi(y,z)}$.

$$E(Y,Z) = \iint_{-\infty}^{\infty} \mathscr{A}(y,z) e^{ik(Yy+Zz)/R} dy dz \tag{3a}$$

The expression for the E field at the point P (Equation 1) rewritten to make use of the apperture function.

We can rewrite this to get rid of the dependence on the distance by subsututing Ky = kY/R and Kz = kZ/R for Y and Z. This gives the final form:

$$E(K_Y, K_Z) = \iint_{-\infty}^{\infty} \mathscr{A}(y,z) e^{ik(K_Y y+K_Z z)/R} dy dz \tag{4a}$$

This is the 2 dimensional Foerier transformation of the aperture function. Thus "the field distribution in the fraunhofer diffraction pattern is the Fourier transform of the field distrubution across the aperture (e.i., the aperture function" [4]).

For the psf we are interested in the intesity which is not the electric field E but $|E|^2$. This means we can calculate the PSF of the vAPP by foerier transforming its apperture function and squaring the result. Note that the amplitude in the apperture function does not only have to depend on the shape of the apperture as there might be partially transparant material. The apperture function does not even have to be an apperture.

With the PSF we know how a single point source would look when imaged by an optical system. If we assume the system is linear system (****isnt it always*****?) we can use the superposition principle to image extended sources by convolving the psf with the extended source.

2.1.1 *Atmorphere*

The telescope or choronograph are the only optical system at play. There are many differently moving layers of air between the telescope and space. These work as independent optical systems that change in time. Each layer moves in a different direction at a different speed as winds are different at various altitudes. This changes the phase of the light. The complete psf changes all the time. The changes are smaller at smaller timescales.

2.1.2 *Adaptive Opics and spechles*

Since the 1990 adaptive optics (AO) are used. These change shape to undo the phase change of the atmosphere. However as these effects are unpredictable they always lack behind slightly. Further more they have errors themself, the phase is never completly corrected. Both these effects cause small distortions in the final image, these are known as spechles. Thus even with AO the total psf for the atmosphere, the AO and the instrument will keep changing in time, however the magnitude of the change is severly reduced. Adaptive optics don not correct the entire field, generally each system has a radius of correction in which the AO works.

-

2.2 VAPP

As mentioned in the introduction the vector apodising phase plate is not a normal coronograph. The apodising phase plate (APP) is a coronograph that changes amplitude of phase in the pupil plane to create destructive interference in an erea of the psf. This creates a very dark area on the psf. Dim object imaged there can be resolved if the contrast between them and the star is smaller then the contrast between center peak of the psf and the dark zone. Because the coronograph works in the pupil plane it is insensitive to the effects of spechles, further more unresolved stars do not limit how close to a star the chronograph can function.

The APP does this by introduces differences in the optical path length thereby changing the phase. These changes are designed to create the mentiond dark zone in the shape of a 180° half circle with a radius of 2 to 9 λ/D [1]. To do so opical the path length differences need to be different throughout the pupil, the design can be seen as a hightmap of path differences. The APP is manufactured by directly printing that heightmap using liquid-crystal technology.

The vAPP is an upgrade to the APP that applies a the path length

2.3 DISKS

A newly formed star is enveloped in a disk of gass and dust, a protoplanatary disk.

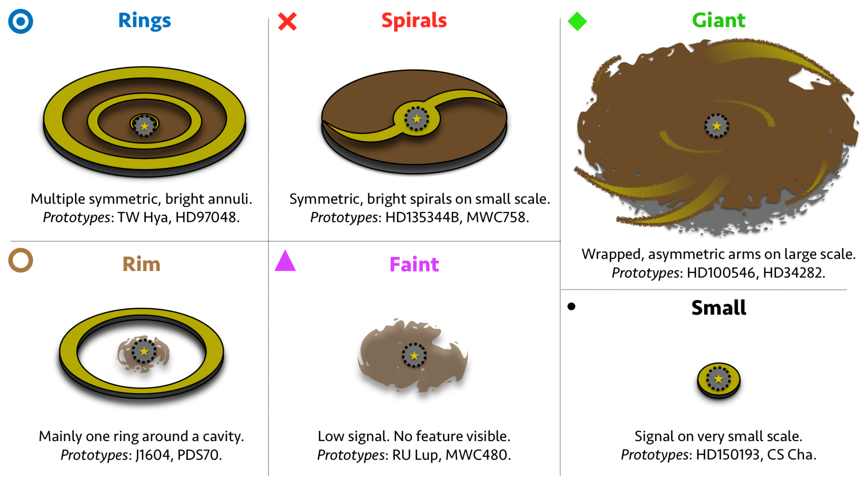
–something about the components/dust/gass refwilliams

From it planets can form. The process of planat formation is not yet understoot. Direct imaging of newly formed planets is hard. Objects inside a disk disturb the shape and create features in the disk. By observing the features of a disk we can learn more about planet formation.

2.3.1 *Catogorisation*

Roughly speaking disks seem to be ring or spiral shaped with some forms in between. [2] classifies them into 6 catogories in Figure 4.

Figure 4: Sketch summarizing the different classifications of protoplenatary disks proposed by /ref



They then conclude that: -faint disks are young -spiral disks are almost starting theire main sequence -ring disk have no outer stellar companion (??)

2.3.2 *Challenging to Obeserve*

It is challanging to observe a disk since its brightness is low compared to the star. To get an upper limit on the brightness of a disk assume all star light that hits the disk is reflected towards us. The light from a star drops quadratically as it gets farther away. Thus we will never have a disk brightness exeeding $1/R^2$. A disk at 1 AU from an run like star will have a brightness 2.1×10^{-5} of the star. At 5 AU this drops to 8.6×10^{-7}.

3 DATA GENERATION

We choose not to use on sky data but create our own. This presents a number of advantages though the main reason is the lack of disk observations using the vApp. Generating the data from a model allows us to vary paramaters as we wish. We can try a reduction method on a simple slightly inclined disk or a near face on disk with many rings. By reducing images of morpholocally differing disks we can map out how well a reduction method works for each morphology. Further more we can clearly separate artifacts created during data reduction from disk features when we know what the disk looks like.

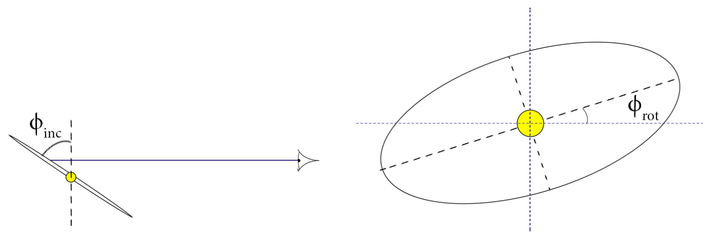
3.1 DISK MODEL

We use a 2-dimensional disk model based on the work by [3]. The model has 4 basic parameters:

INCLINATION The angle the disk is tilted towards the observer. A 0 degrees inclination gives a face on disk and 90 degrees a horizontal line being an edge on disk. As illustrated in ??

POSITION ANGLE After inclination the disk can be rotated around the line of sight from the observer, rotation to the left is positive. See ??

INNER AND OUTER RADIUS Many disks start and stop at some radius from star. The inner and outer radius are relative to the field size that defaults to 10. An Inner radius of 2 gives a hole in the disk with a diameter 20% of the image width.

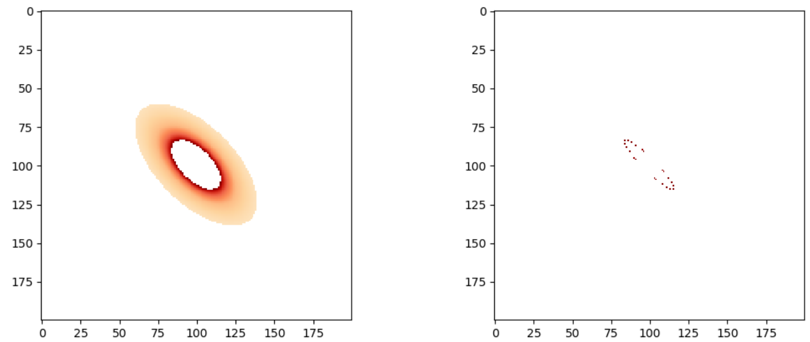


(a) Inclination angle from: [3] (b) Position angle, from: [3]

The disk is modeled as optically thick and does not emit light on its own. At a certain radii between the inner and outer radii the disks brightness is given by:

$$B(r) = B_{star} \cdot \left(\frac{r}{R_{star}}\right)^2 \tag{5}$$

We rasterize the image onto a resolution of 200 by 200 pixels. This not only speeds up our calculations it also is the expected output of an actual observing session. The model behaves well for most disks however on this resolution features that are small in the observers plane are pixilated as we see in Figure 6 below. This poses no problem as we do not expect to resolve such features.



(a) model output for an inclination of 60 deg, an inner radius of 2 and an outer radius of 5

(b) model output for an inclination of 80 deg, an inner radius of 2.2 and an outer radius of 2.3

Figure 6: two disks created by the model with different size and inclination both with a position angle of 45 degrees

3.2 PSF GENERATION

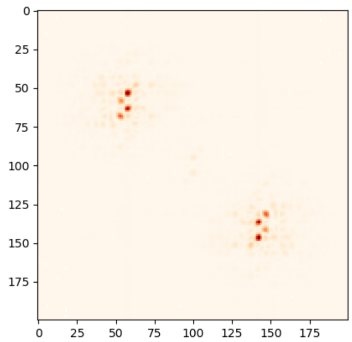
To simulate an observation do not use a single psf as given by /cite-vApp as during an observation the combined psf of the atmosphere and instrument changes. A complete simulation of these effects is out of the scope of this thesis. We instead decided to try and approach a similar morphology to the on sky psf.

First we tried modifying a give single vApp psf to get a set of disturbed psfs. To achieve this a pattern is added to the foerier transform of the psf before transforming it back from foerier space, see the equation below. The pattern is then shifted for every timestap.

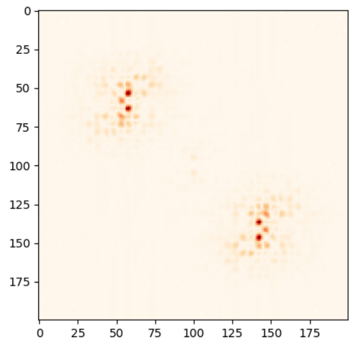
$$\mathscr{F}_{2d}^{-1}\left(\mathrm{intensity} \cdot \mathscr{F}_{2d}(\mathrm{psf}) \cdot \mathrm{pattern} + (1 - \mathrm{intensity}) \cdot \mathscr{F}_{2d}(\mathrm{psf})\right) \tag{6}$$

The best results where achieved using a grid of blurred circles as pattern, see Figure 7. Note the distortions to the psf are clusterd around the center of its peaks but not randomly spread. Clearly this will not do.

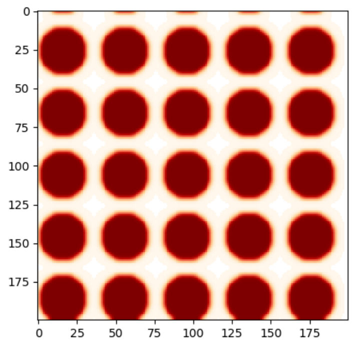
Then we tried a simulation of the psfs using HCIPy, an open-source object-oriented framework written in Python for performing end-to-



(a) difference between two psfs created using this method, the pattern has shifted 10 pixels



(b) difference between two psfs created using this method, the pattern has shifted 5 pixels



(c) pattern that is shifted and applied to the foerier space of a psf

Figure 7: Pattern (a) and the diffrences between psfs **distorted** with this pattern using the method described above

end simulations of high-contrast imaging instruments [5]. The framework is used to do a very rough simulation. We use the provided methods to create a multi-layer atmospheric model that changes in time. Then we use that model, the vApp amplitude and vApp phase screen to generate a series of psfs. Instead of modelling an active optics system we modified the fried parameter for the atmosphere to get similar morphological changes in time to the availible on sky images. This is sufficient as the disk will always lie within the .....radius of correction???..... which means the limiting effect of an AO system on the disk will only be a increase in resolution by reducing the seeing effect.

Wu use a telescope diamater of $8.2 meters$ and a wavelength, of $1 \cdot 10^{-6} meters$ for the simulation. We got the right morphology with a fried paramater of 4m. To put this into perspective: to simulate excellent seeing conditions we would use 20cm. With these setting we use hcipy to create an orderd set of psfs changing through time as the simulated atmosphere evolves. See Figure 8 for the diffrence between the first psf in a set and later psfs in the same set. Note that as time evolves the differences grow.

3.3 COMBINGING

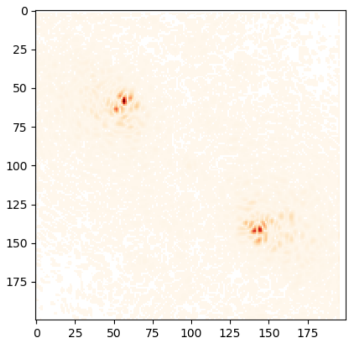
To get a dataset that simulates an obeservation we create an orderd set of disk images each one rotated a bit to eachother. This accounts for the field rotation caused by observing with an alt azimuth telescope. Now to get the simulated observation an orderd set is created by convolving each n-th image from the disk set with the n-th image of the psf set. These are the simulated observations through time.

Using variations on this method we create 3 different sets.

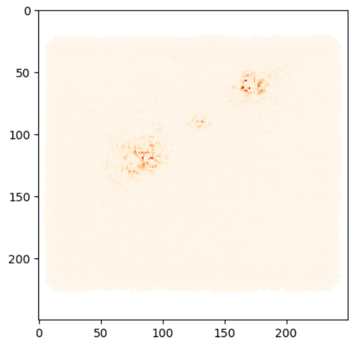
1. Place a single pixel with value one in the center of the disk before going through the above procedure. This is our observation set.

2. Swap the disk with the single pixel in the center representing the star. This set we use to check what artefacts are created by the reduction

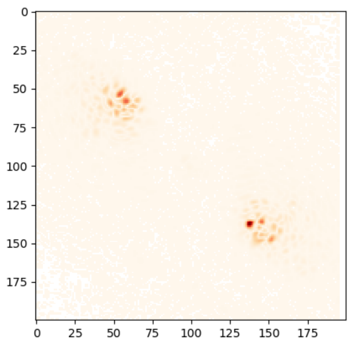
3. Take the convolution of the n-th disk image with the first psf image of the psf set. This way we lose all atmospheric effects, since we havent placed a star in the center we see only te effect of the vApp on the disk image.



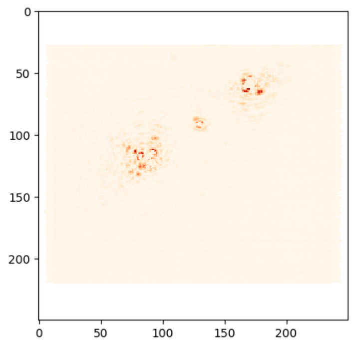
(a) simulated psf: 1e - 2e, 0.7 seconds difference



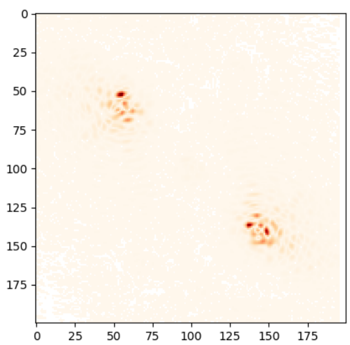
(b) on sky psf: 1th - 2th, *** seconds difference



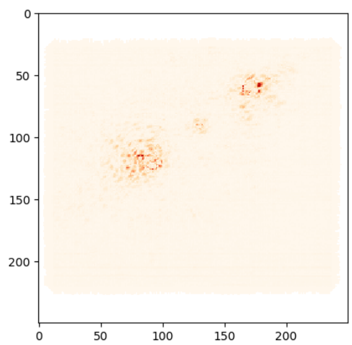
(c) simulated psf: 1th - 10th, 7 seconds difference



(d) on sky psf: 1th - 10th, *** seconds difference



(e) simulated psf: 1th - 50th, 14 seconds difference



(f) on sky psf: 1th - 50th, *** seconds difference

Figure 8: Differences between the first psf of an observation and later psfs. Compared between simulated observations on the left and on sky data on the right. The psfs where aligned then normalised on the maximum of the leakage term, finally the absolute value of the diffrence between the first and n-th psf was taken. The second, 10th and 50th simulated psf are 0.7, 7 and 14 seconds apart in the simulation

[1] David S. Doelman, Frans Snik, Nathaniel Z. Warriner, and Michael J. Escuti. "Patterned liquid-crystal optics for broadband coronagraphy and wavefront sensing." In: *Proceedings SPIE 10400, Techniqes and Instrumentation for Detection of Exoplanets VIII* (2017).

[2] Antonio Garufi et al. *Evolution of protoplanetary disks from their taxonomy in scattered light: spirals, rings, cavities, and shadows*. Oct. 2018.

[3] Okko van der Haak and Pieter Speelman. "Stellar disk reconstruction using Spectro-polarimetry." Bachelor Thesis. June 2018.

[4] Eugene Hecht. *Optics. International Edition*. 2002.

[5] E. H. Por, S. Y. Haffert, V. M. Radhakrishnan, D. S. Doelman, M. Van Kooten, and S. P. Bos. "High Contrast Imaging for Python (HCIPy): an open-source adaptive optics and coronagraph simulator." In: *Adaptive Optics Systems VI*. Vol. 10703. Proc. SPIE. 2018. DOI: `10.1117/12.2314407`. URL: `https://doi.org/10.1117/12.2314407`.