Magnetic Resonant Pulsed Pumping of Rubidium

by

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Acknowledgments

Thanks to everyone!

Abstract

My abstract goes here.

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1 Introduction

In 1609, Galileo Galilei used a device of two lenses at the sky, seeing for the first time with magnification the imperfections on the moon, small objects orbiting Jupiter, and even the phases of Venus [NAS03] [Obs09]. With observations from this crude contraption, Galileo showed that at least one planet was orbiting the sun. This evidence was able to support the theoretical model of a heliocentric universe, proposed in the sixteenth century by Nicolaus Copernicus and expounded upon by Johannes Kepler in the next century [JH01]. As time progressed, inquisitive minds began to wonder what else could be discovered with the power of magnification. Telescopes, as they would be coined, began a rapid period of advancement. Lenses were made larger in diameter in order to view fainter objects. Optical components were fabricated with less imperfection allowing for better resolution. Curvature and indices of refraction of lenses were exploited, allowing for immense degrees of magnification. Achromatic, aspheric, and cylindrical lenses were created, ridding telescopes of many aberrations. By the late twentieth century, telescopes were as optically perfect as they could be; no advancements in optics would allow them to see with greater magnification or increased resolution. However, there was one lingering problem.

Light can be approximated as a ray. This means that as it travels through free space, it travels in a straight line without deviation from its path. Suppose, however, that this ray of light travels from free space into a region of gas. Will the ray continue to travel in a straight line as it passes through the gas? The solution to this problem is the famous Snell's Law, given in equation 1.1,

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{1.1}$$

where n_1 is the index of refraction of the first medium, n_2 is the refractive index of the second medium, and θ_1 and θ_2 are the angles that the ray makes with the normal to the medium. This tells us that the ray will not continue in a straight line, but will bend, or *refract*. A schematic of this is shown in figure 1.1.

Returning to the idea of telescopes, light that is emitted from a distant star or reflected off a moon or planet will essentially travel through free space for

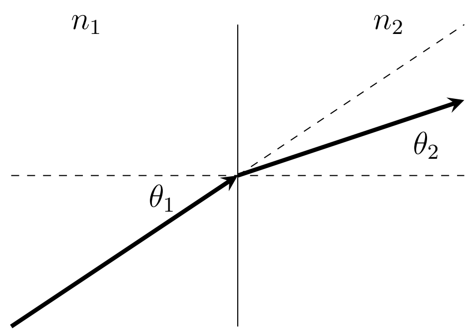

Figure 1.1: Schematic of a ray of light refracting according to Snell's Law as it passes from one medium into another.

the majority of its voyage. However, as it nears Earth, it begins to enter the atmosphere that surrounds Earth, and refracts according to Snell's Law. It may seem that this refraction is the same for all rays of light and thus does not result in any imperfections when imaging with a telescope, but this is not true due to the inhomogeneity of the atmosphere. There are two main concerns here: The first issue is that the index of refraction depends on many parameters such as temperature, pressure, and density. The second issue is that the atmosphere of the Earth is not constant in these parameters, but fluctuates slightly over time. These two properties indicate that light will not refract uniformly as it passes through the atmosphere, but will be distorted due to fluctuations in the index of refraction. This is known as atmospheric distortion.

In order for telescopes then to receive clearer images, astronomers need to find a way to rid their systems of this atmospheric distortion. One way to do this is to put a telescope outside of Earth's atmosphere where it would be unaffected by atmospheric distortion, which this was done with amazing success in 1990 with the low-orbiting, powerful Hubble Telescope. However, it is not only extremely costly to put telescopes into orbit, but also difficult pragmatically as they cannot be easily maintained or serviced.

Thus, a different solution was posed. If the astronomers could somehow model how light was distorted as it passed through the atmosphere, they could then subtract those distortions out of their images and obtain clearer data. This would be done By observing a point source in the sky, such as a distant star, and, with knowledge of how a point source would ideally be imaged through their telescope, they could compare the distorted image of the point source with what the point source would ideally look like and correct their data.

This process became known as adaptive optics and is used by many ground-based telescopes around the world. Telescopes observe a distant star, or a man-made "laser guide star," compare it to an ideally imaged point source, and move a deformable mirror to subtract out distortions. The deformable mirror is composed of many smaller mirrors, each of which can moved precisely, usually by a piezo-electric controller. This allows any phase to be added onto the obtained image. Thus, by finding the phase of the aberration present in the obtained data be comparison with an ideal point source, the conjugate of that measured phase can be added on to the data, effectively cancelling out the distortion [PW06]. This is normally done in real time, allowing for constant image restoration. The result is crystal clear images without atmospheric distortion.

A problem with this is that there is not always a star in the telescope's field of view. To rid this problem, artificial stars, called *laser guide stars* were constructed. Laser guide stars are created by sending laser light into the atmosphere, where it interacts with a layer of sodium atoms [PW06]. When the wavelength of the laser light is resonant with sodium's absorption spectrum, the atoms will absorb and emit this laser light, creating a glowing blob in the sky. This glowing blob of atoms is used as the laser guide star.

There are two main challenges that come with creating a laser guide star: the brightness and shape of the star. It is important for the star to be bright enough that the telescope system is able to pick up enough light. The shape of the star is also important as it must be as near to circular as possible in order to compare it with an ideal point source. The shape of the star comes mostly from beam profile, which will not be addressed in detail here.

In order to create a brighter laser guide star, a few methods are employed. One method is to increase the intensity, the power per unit area, of the laser. This will allow for more atoms to absorb and emit light, thereby creating a brighter star. Another method is to increase the diameter of the laser beam, which will allow for a greater area of sodium atoms to be reached by the light. A more sophisticated method, which will be detail in **Section **, is called optical pumping, and makes use of circularly polarized light to exploit a quantum mechanical state of the atom's energy levels.

In this paper, we explore an untested method, called *magnetic resonant pulsing*, to increase the brightness of laser guide stars. Magnetic resonant pulsing requires atoms to be pumped with laser light of repetition rate equal to that of the atom's Larmor frequency when exposed to a magnetic field [TJK14] [RR10]. In our experiment, we use measure the absorption spectra of rubidium, an atom similar to sodium, with pulsed light in a magnetic field to test this proposed method.

2 Background

Laser guide stars (LGS)[1] are invaluable instruments in modern astronomy, allowing observations of extremely high resolution to be made even in unfavorable atmospheric conditions. In this chapter, we describe LGS in more detail, the optical processes involving light and atoms, and a common laser used for LGS, the dye laser.

2.1 Laser Guide Stars

This section feels repetitive given my introduction

As mentioned earlier, telescopes have evolved physics to their prime, at which almost no amount of physical improvements, e.g. lens size, component purity, alignment, will allow improved resolution. Any distortions at this point come from atmospheric distortion, which is the random bending and distortion of light as it passes through Earth's atmosphere. Light coming from distant astronomical sources can be very well approximated as a plane wave with zero distortion. However, as this plane wave enters Earth's atmosphere, it diffracts according to Snell's Law, shown in Figure 1.1. Due to the inhomogeneity of the atmosphere, the wave is not distorted uniformly, but randomly. This process is shown in Figure 2.1.

In order to account for this atmospheric distortion, astronomers make use of the well defined way in which point sources are imaged through optical systems. When an idealized point in imaged through an optical system, it has a certain energy distribution in image space, known as the point spread function. However, any distortions in a system will be present in the point spread function, thus giving a way to measure the distortion in a system.

It turns out that stars are very close to being idealized point sources. Thus, when making observations, astronomers can also observe distant stars and mea-

[1]LGS will refer to both the plural and singular of the word, e.g. "LGS are frequently used in modern astronomy" and "LGS systems consist of many components." Context should provide the correct form throughout reading this paper.

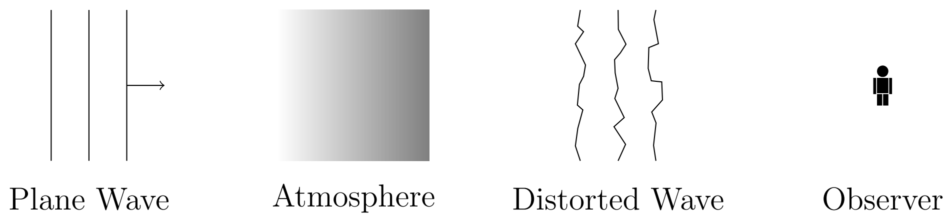

Figure 2.1: Atmospheric distortion of a plane wave passing through Earth's atmosphere

sure the point spread function they create when imaged through their telescopes. Since the light from these stars is passing through Earth's atmosphere, it will be distorted, and show up in their point spread function.

Astronomers use a combination of Fourier mathematics and precisely deformable mirrors to first estimate the distortion and then "subtract" the distortion from the image. This is done by measuring the distorted point spread function, creating an estimated point spread function, and then adding distortion into the estimated point spread function until it matches the observed point spread function [Gon82]. Once this is completed, the amount of distortion added to the point spread function is forwarded to the deformable mirror, where it creates a conjugate wavefront (essentially the negative of the distorion). The image the telescoping is taking is reflected off this mirror, thereby removing any distortion. A more in-depth treatment of adaptive optics is taken in Appendix A.

All that is left is for the astronomer to find the star he or she wishes to be the guide star. Sometimes there is conveniently a star bright enough in the field of view that can be used as the guide star. However, often there is not a star bright enough in the field of view, leaving the adaptive optics system useless. This is where an artificial guide star, or LGS, is useful.

2.2 Light, Atoms, and Interactions

Approximately 60 km in the atmosphere lies a 10 km thick layer of sodium atoms. These atoms come from meteorites as they burn up in Earth's atmosphere, leaving behind their composite particles, a significant portion being sodium metal [Kib09]. The density of this sodium layer varies throughout a given day and throughout the year, but typically is near 5×10^{13} atoms/m^2 [Kib09]. These atoms form the basis of LGS systems.

As dictated by quantum mechanics, atoms have unique, quantized energy levels. For now, we will ignore various complications such as spin, magnetic field, and orbit coupling. The various energy levels thus come from the distribution of the electrons in the atom, known as electronic states. Atoms want to be in the most stable state with their electrons in lowest levels. However, electrons are free to make transitions between these levels as long as energy is conserved during these transitions.[2] In order for an electron to transition from one level to another, the atom most absorb or emit an energy equivalent to the energy difference between the two levels.

Although atoms in excited states seek to decay to a state of lower energy,we want to know how. Experimentally, we have seen that a common process for an excited atom to decay in is the emission of a photon. However, energy must still be conserved. From modern physics, the energy the photon is

$$E = h\nu \tag{2.1}$$

where h is Planck's constant and ν is the frequency of the emitted photon. Hence, by measuring the frequency of a photon emitted from an atom, we can measure the energy corresponding to electronic transitions in an atom. More importantly, this process is reversible, meaning we can excite the atom by sending a similar photon to the atom; that atom will shortly decay be emitting another photon. This is the foundation of a LGS — laser light of frequency corresponding to that of sodium is shone onto the atoms in the atmosphere, the atoms absorb this light, and then shortly emit this light in random directions, creating a "globe" of light.

The first correction to this simplified model is that of the fine structure. The fine structure describes the splitting of the ground energy state due to the spin of the electron and relativistic nature of the particles. Spin is an intrinsic quantity particles possess, and electrons are spin-$\frac{1}{2}$ particles, meaning they can have spin $S = \pm\frac{\hbar}{2}$. This spin interacts with the orbit of the electron, thereby changing the energy level. The second correction comes from replacing the classical kinetic energy term in the Hamiltonian with the relativistic kinetic energy term [Kib09]. These two corrections effectively split the ground state energy into to distinct, but close, energy levels. This splits the sodium ground state into to levels, creating two distinct transitions, from $3p_{\frac{3}{2}}$ to 3s and $3p_{\frac{1}{2}}$ to 3s; these transition have respective wavelengths 588.99 nm and 589.59 nm.

The next quantity to examine is angular momentum. Photons can carry spin angular momentum (SAM), which can be exchanged with the atom when it is absorbed. When an atom absorbs a photon with SAM of $J = \pm\hbar$, the angular momentum of the atom must increase by the same amount $\Delta m = +\hbar$. However, when the atom emits a photon, it can decay to any state satisfying $\Delta m = \pm\hbar, 0$. This is shown in Figure 2.2.[3]

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[2] We will address other conserved quantities, such as angular momentum and spin, shortly.

[3] "Spin polarization by optical pumping," Colinear Laser Spectroscopy, 2013

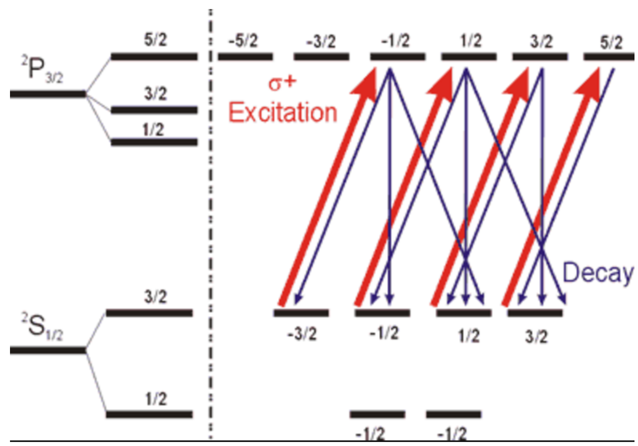

Figure 2.2: Figure of optical pumping in which the excitation of the atom results in an angular momentum change of $\Delta m = +1$ but decay governed by $\Delta m = \pm 1, 0$.

Exciting atoms with circularly polarized light tends to push atoms towards a state with a stable cycle of absorption and emission where the atom absorbs a photon, undergoing a change $\Delta m = +1$, and then decays by $\Delta m = -1$ since this is the only possible state to decay to. This is seen in Figure 2.2 as the transition between the two right most states. Furthermore, this transition has the highest photon return and highest cross section [Kib09], giving a stronger reason to use this process for LGS.

We must also address the interaction the atom may have within a magnetic field. The first issue that arises is the precession of the atom in the magnetic field due to the magnetic moment of the atom; the precession is known as Larmor precession with a frequency known as the Larmor frequency. This precession actually has negative effects as it causes a reorientation of the atom's angular momentum before the stable transition of optical pumping can be established [TJK14]. The size of this effect is determined by the strength of the magnetic field and the orientation of the magnetic field with respect to the incoming light: the stronger the field and the more perpendicular the orientation, the more negative the effects on optical pumping it has.

However, a magnetic field also splits the energy levels of the atom, similar to the splitting due to the fine structure. The splitting is known as the Zeeman effect, and is a much smaller split than that of the fine structure. It turns out that the lifetime of an electron in an excited Zeeman state is equal to frequency of the atom's Lamor precession.[4] It has thus been proposed by Kane et al. that exciting atoms with light pulsed with a repetition rate equal to that of the Larmor frequency of the atom in the magnetic field can mitigate the negative effects of

[4]This is what you (Michaela) told me; I don't completely understand this nor can I justify it.

the magnetic field on optical pumping. This is due to the fact that light pulsed at this frequency would only interact with the atom at one point in the atom's Larmor precession, and could thus maintain the benefits of optical pumping since the atom's angular momentum would not be reoriented as it would without this pulsing.

2.3 Dye Lasers

Dye lasers were some of the first lasers to be used as laser guide stars. This is due a variety of factors: their wavelength can be precisely tuned over a broad spectral range, they are relatively cheap and easy to use, and they are fairly robust. In the modern age, many telescopes have opted for solid state and diode lasers with improved properties such as lower divergence and narrower linewidth. Nevertheless, dye lasers will be explained in this section because of their pedagogical importance and relevance to this project.

Laser is an acronym for *light amplification by stimulated emission of radiation*. In general, a laser consists of three parts: a pump, a medium, and a cavity. The pump provides enough energy to excited atoms in the medium into the excited state. The atoms then decay down into their ground state, releasing a photon in a random direction, known as spontaneous emission. However, if a spontaneously emitted photon comes into contact with another excited atom, it can cause that atom to decay and release a photon with the same direction and frequency it has; this is known as stimulated emission. If a cavity is created around the medium, possibly by placing mirrors on either side of the medium, photons will travel back and forth in the medium, stimulating the emission of more and more photons. These photons will continue to build, creating a powerful source of monochromatic, coherent light. One of the cavity mirrors can be made partially transmissive, which will allow only a certain percentage of photons to pass through.This is the foundation of a laser.

A dye laser works in exactly the same way. Its medium is a fluid of florescent dye in a solvent, such as alcohol. The pump is commonly another laser with a frequency of light corresponding to the absorption wavelength of the dye molecules. The cavity can vary in design, but normally consists of a mirror at one end and a diffraction grating at the other [JES97].

The main advantage of dye lasers are their incredible tunability over a broad spectral range. This is a consequence of medium being dye molecules, which a relatively large chain molecule. Once excited by the pump, these molecules can relax in energy due to the many vibrational and rotational states they can reside in. These relaxations result in photons of varying wavelength being emitted spontaneously. In order to access and select these different wavelengths, a diffraction grating is placed at one end of the cavity. This allows the varying wavelengths to be split apart, and the desired wavelength can be chosen and sent back into the medium where it will stimulate the emission of more photons of equal wavelength. Dye lasers can typically have tunability over close to 100 nm [JES97].

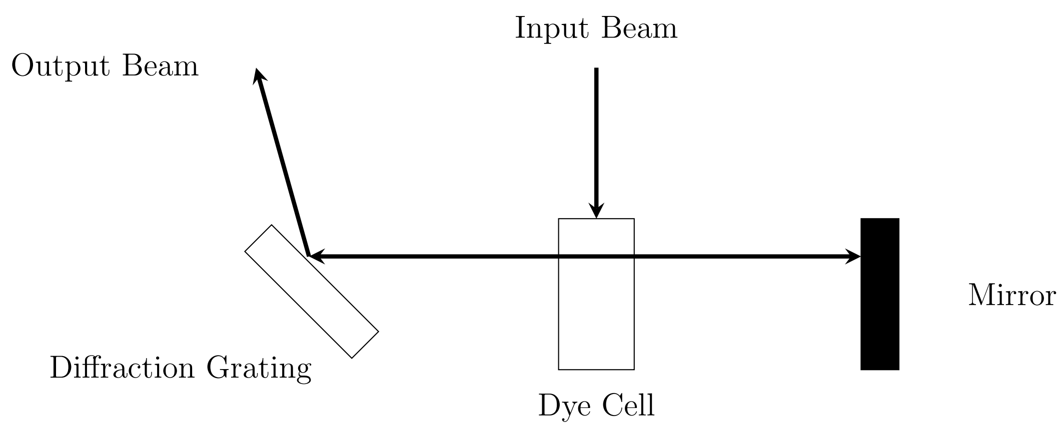

Figure 2.3: Schematic of a dye laser with dye fluid in the dye cell being pumped by a laser input beam and lasing in a cavity consisting of a mirror and diffraction grating.

3 Laser System

3.1 Duetto Laser

rep rate, pulse length, power, energy, about

3.2 Second Harmonic Generation

crystal, properties, theory, data about resistance and conversion eff.

3.3 Dye Laser Cavity

Critical length, methods of alignment, dual pumping? Wavelength and tunability

4 Magnetic Field Housing

Calculate gyromagnetic ratio, larmor frequency, magnetic field required, current required, geometry, testing, magnetic field data, homogeneity stability

5 Absorption Spectroscopy

absorption spectroscopy of rubidium with pulsed dye laser. Show difference in absorption (or no difference) when repetition rate is equal to that of the larmor precession (determined by magnetic field)

6 Conclusion

Conclude everything, did it work, did it not work, where should people go next, what is the significance

A Adaptive Optics

In order to account for this atmospheric distortion, astronomers make use of the well defined way in which point sources are imaged through optical systems. When an idealized point in imaged through an optical system, it has a certain energy distribution in image space, known as the point spread function. For an optical system with spherical symmetry and no aberration, the point spread function can be described mathematically along one coordinate as

$$P(x) = \frac{J_1(x)}{x} \tag{A.1}$$

where $J_1(x)$ is the Bessel function of first kind. This function is known as the Airy Disk and is shown in Figure A.1; it is an idealized description of a point imaged through a perfect optical system.

It turns out that stars are very close to being idealized point sources. Thus, when making observations, astronomers can also observe distant stars and measure the point spread function they create when imaged through their telescopes. Since the light from these stars is passing through Earth's atmosphere, it will be distorted and these distortions will show up in the point spread function, thus deviating from the Airy Disk described by Equation A.1.

Astronomers use a combination of Fourier mathematics and precisely deformable mirrors to first estimate the distortion and then "subtract" the distortion from the image; this method follows that outlined by Gonsalves [Gon82]. The phase of the distortion can be described as a summation:

$$\theta(\omega) = \sum_{k=0}^{\infty} c_k \phi(\omega) \tag{A.2}$$

where $\{\phi(\omega)\}$ is a set of polynomials and c_k is a coefficient that quantifies how much of each polynomial is present in the distortion. This phase can then be used to create a point spread function that would model a system with that certain distortion. This is done by first calculating optical transfer function

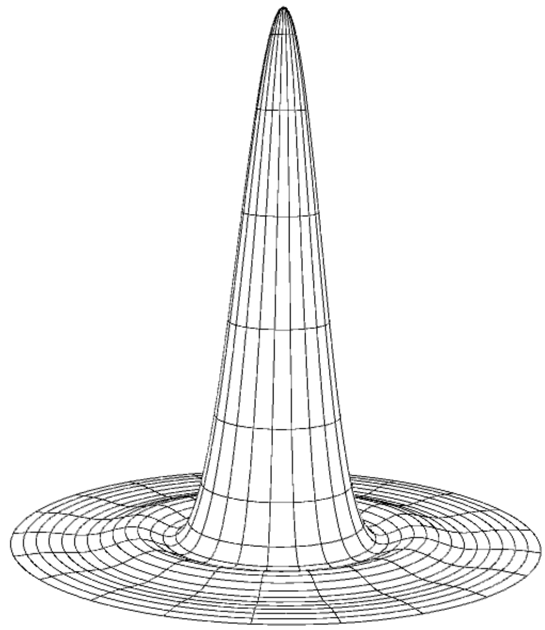

Figure A.1: Graph of the Airy Disk function, describing an idealized point imaged through a spherically symmetric, aberration free optical system

$$H(\omega) = A(\omega)e^{i\theta(\omega)} \tag{A.3}$$

where $A(\omega)$ is the aperture function[1] of the system and $\theta(\omega)$ is the phase described above. Taking the inverse Fourier transform and then the modulus squared, we arrive at the point spread function

$$P(x) = \left| ifft[H(\omega)] \right|^2 \tag{A.4}$$

where $ifft$ denotes the inverse Fourier transform of the argument. Thus, while taking observations can also observe the distorted point spread function of a star, iterate through many different polynomials until the estimated point spread function is similar to the observed point spread function, and then an estimate of the phase of the distortion is known [RQF91].

Searching for the correct polynomials weighted by the correct coefficients is not trivial. Sometimes certain polynomials can be ignored if it known by symmetry

[1] The aperture function is normally a function describing where light can and cannot pass through. For a circular aperture, it would consist of a solid circle where light can pass through and nothing around the circle indicating light out here does not show up in the point spread function.

that they will not show up in the point spread function. Regardless, searching for the correct distortion is an optimization of a function in a huge parameter space. Typical algorithms use a steepest descent approach, which changes one parameter at a time, calculates an error between that estimation and the observed point spread function, and seeks to minimize this error. There have also been algorithms that use random searches, Monte Carlo walks, and Markov chain Monte Carlo searches that claim robustness and speed.

An example of this is the problem of reducing an unknown aberration in an optical system. Say, for example, you bought a huge lens for your telescope. You set it up, and look at Venus, but upon looking at it, you realize while the center of Venus is in focus, the edge is out of focus, or vice versa. You realize your new lens has spherical aberration (thanks to the manufacturer), but you need to collect data and a new lens won't be ready in time. Miraculously, you have a deformable mirror lying around, and decide to try your hand at adaptive optics.

You then find a nice star and take a picture of it with your telescope. Using the Zernike polynomials described in Equation A.5, which describe most common aberrations in typical optical system; you calculate the Z_4^0 Zernike polynomial corresponding to spherical aberration.

$$
\begin{aligned}
Z_n^m(\rho,\phi) &= R_n^m(\rho)\cos(m\phi)\\
Z_n^{-m}(\rho,\phi) &= R_n^m(\rho)\sin(m\phi)\\
R_n^m(\rho) &= \sum_{k=0}^{\frac{n-m}{2}} \frac{(-1)^k(n-k)!}{k!(\frac{n+m}{2}-k)!(\frac{n-m}{2}+k)}
\end{aligned}
\tag{A.5}
$$

From here, you create a point spread function with varying amounts of spherical aberration by weighting this Z_4^0 by different amounts. The algorithm doesn't take too long, since you only have one parameter to tune. Once you get a point spread function similar to the one of the observed star, you declare you have found the aberration in your lens! You then create this distortion in your deformable mirror, reflect the image of Venus off of this mirror, and collect your data.

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