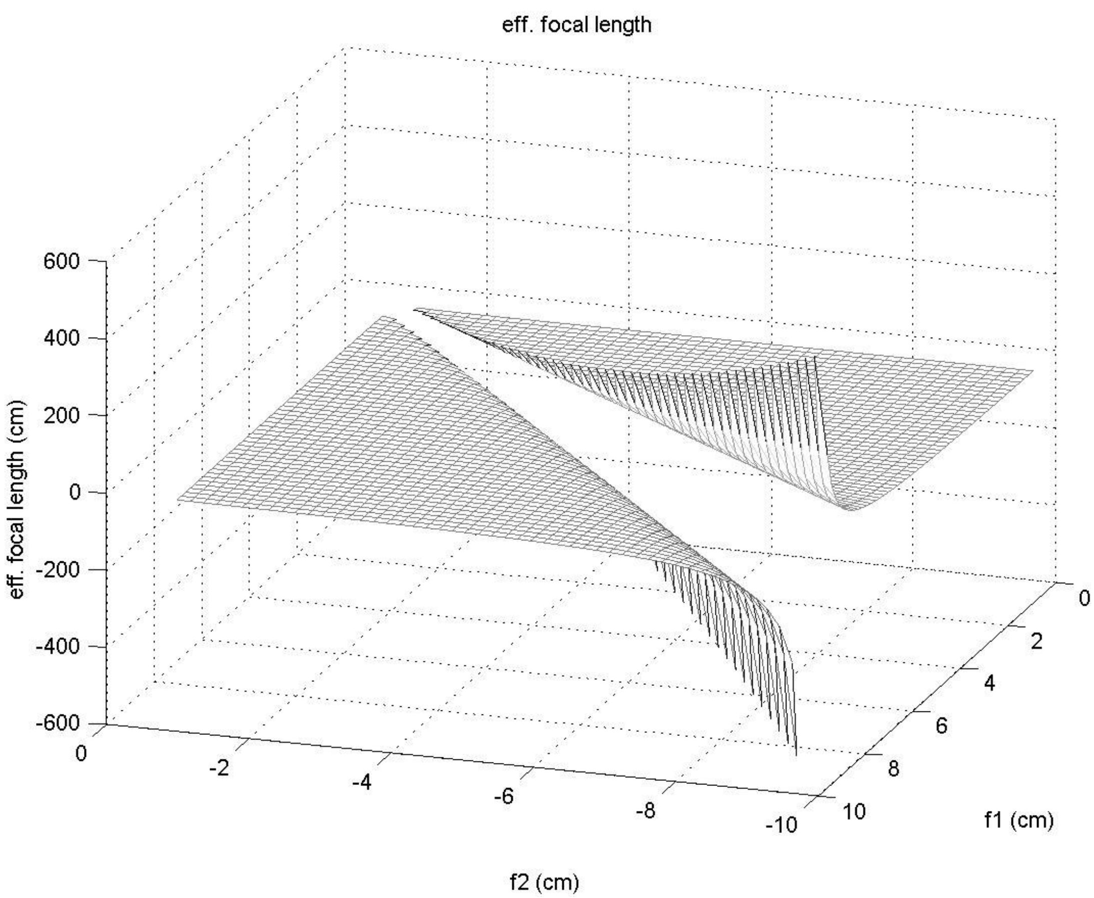
Camera Obscura

ECEN 5616: Optoelectronic System Design - Prof. Robert McLeod – Fall 2006



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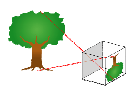
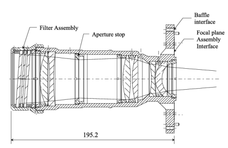
1. Objectives

- To analyze the need-based-evolution of the camera from a pinhole camera[1] (5th century BC) to a plenoptic camera[2] (2005)
- To design a contemporary digital camera

2. Evolution 

In the first part of the project, an attempt will be made to throw light on the factors that motivated the evolution of the camera. Specifically, the following stages will be considered:

- Ancient - Pinhole, Daguerreotype, etc.
- Medieval - Film, celluloid, etc.
- Contemporary - Digital, SLR, etc.
- Upcoming - 3D

3. Contemporary digital camera design 

The second part of the project will rigorously analyze the design of a present day digital camera. The following questions (and many more) will be analyzed.

- Is a digital camera <u>really</u> better that a film camera? *(Resolution analysis)*
- Why is a "good" camera expensive? *(Multi-lens aberration correction)*
- 1, 2, 3,..10 Mega pixels... Does this "number" have a fundamental limit? *(Diffraction)*
- F/#, NA, DOF, Resolution, Focal length, #Mega Pixels. Why so many parameters?
- Why don't ultra high resolution cameras have a long depth of field? *(Ray analysis)*
- Why aren't monochrome cameras extinct? *(Bayer analysis)*
- Why can a camera zoom in/out when our eyes cannot? *(Significance of distance)*
- What is all this hype about SLR cameras? *(Single lens reflex)*
- Can a "passive" camera capture the 3rd spatial dimension? *(3D field detection)*
- Are two successive images of the same object identical? *(Noise)*

12/16/06

Introduction

This project has two parts. The goal of the first part of this project is to analyze the need-based-evolution of the camera. It is interesting to see how the camera design evolved from a simple (yet elegant in some aspects like extended depth) pin hole design to multi element, multi thousand dollar, aberration corrected, zoom enabled SLR design. Significant breakthroughs in science might often appear as sudden developments to an outsider; but, for an insider, breakthroughs are largely gradual developments that depend heavily on the past research done in the field. Having said that, the motivation for this part of the project is not only to just look into the past, but also to possibly foresee where the field of camera lens design is marching towards.

In contrast to the first part of the project, which would largely be an overview of camera evolution, the second part of the project would focus deeply on designing a contemporary multi-element digital camera, with rigorous aberration and design analysis. Initially, paraxial designs would be performed manually, and later on, thick element aberration analysis would be performed with ZEMAX.

The forthcoming pages are organized in the following way: Section 1 analyzes camera evolution, Section 2 rigorously designs a digital camera, Section 3 has conclusions, Section 4 has acknowledgements, Section 5 provides a list of references, and Section 6 (Appendix) has the MATLAB code used for this project.

1. Evolution

1.1 Pin-hole camera

A pinhole camera (Fig. 1) is nothing more than a fully closed box (whose interiors are typically painted black) with a small ("pin" sized) hole. A light sensitive material (film) placed on the side opposite to that of the pinhole records an inverted image of the object (any thing in front of the pinhole that scatters incident light)

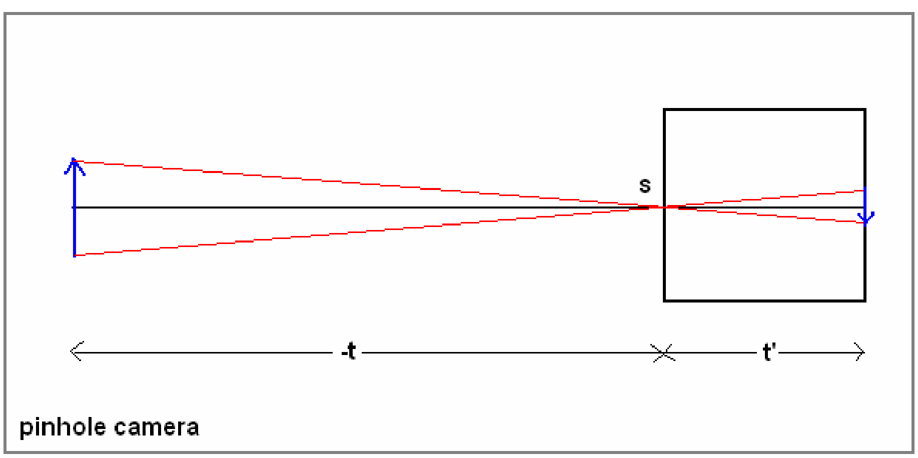


Fig 1: Pinhole Camera

Some pros and cons of a pinhole camera are listed below:

Advantages	**Disadvantages**
Easy to make	Time taking
Amazing depth of field	Bad resolution
"No" aberrations	Cannot zoom in/out

Pinhole Camera Design:

The light sensitive screen should necessarily be placed in the far field. Specifically, the z-distance between the pinhole and the camera is tightly related to the size of the pinhole and wavelength of light in the following way.

$$t' > \frac{s^2}{\lambda} \qquad 1.1$$

t'- image distance
s - pinhole diameter
λ - wavelength

The magnification is the ratio of image to object distances. Once t' is fixed, the diameter of the pinhole (**s**) is restricted by equation 1.1, or vice versa.

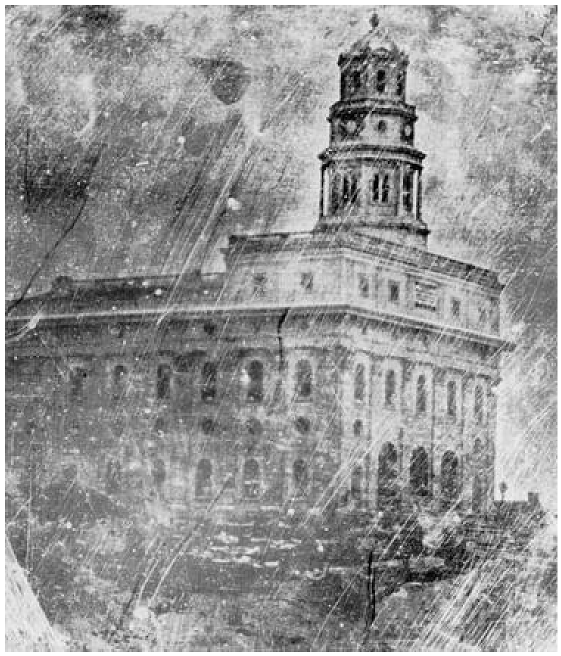
Courtesy: http://www5a.biglobe.ne.jp/~m-tado/image%2000.jpg

The above photograph was taken with a pin-hole camera. Note that even though the resolution is not all that great, the depth of field is amazing! (In fact, several orders better than non-WFC[3] enabled contemporary cameras.

1.2 Daguerreotype

Daguerreotype is a “positive only” detector, which can be used on almost any imaging system (no specific lens design. Since there is no “negative”, images stored on a Daguerreotype cannot be reproduced directly. This was typically used with early pinhole cameras.

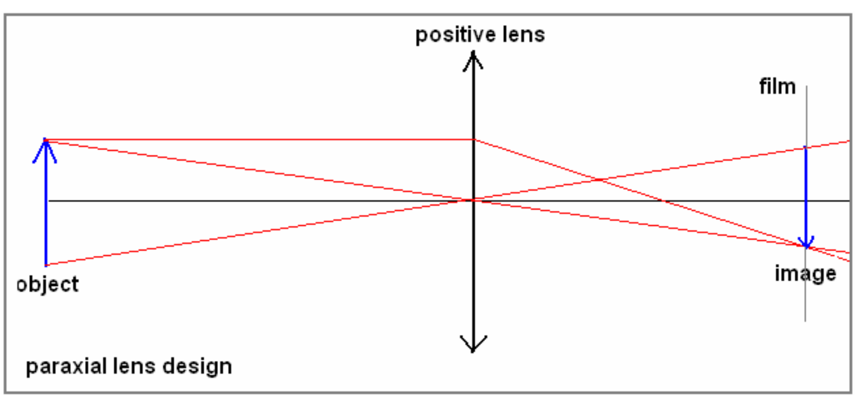
Silver plates were exposed to iodine fumes to form a thin light-sensitive coating of silver iodide. The plates, which typically should to be used within an hour of coating them, are exposed to light for 10 to 20 minutes, depending upon the light available. The plates are later developed by exposing them to mercury heated to 75 degrees Centigrade. The entire process of capturing and developing would take at least an hour! No wonder, people wanted something better!!



A heavily scratched Daguerreotype
Courtesy: http://users.marshall.edu/~brown/nauvoo/nt-d003.html

1.3 Film, Celluloid cameras

- Developed to overcome the disadvantages of pinhole camera. (Resolution, speed)



- But, they ended up compromising on the advantages of a pinhole camera! (DOF, simplicity)

- It is from this stage of the camera evolution, lenses were predominantly used for imaging. Though the use of lenses is good in some aspects (resolution, speed, etc), these advantages invariably were plagued by aberrations. Some of these aberrations (like chromatic) were due to the inherent properties of the materials used for making lenses, while many others were because of the "spherical" shape of the lenses. In order to correct these aberrations, the use of multi-element lens design became almost inevitable, and consequently, the cost of "good" (aberration-less, high resolution) cameras had a steep rise.

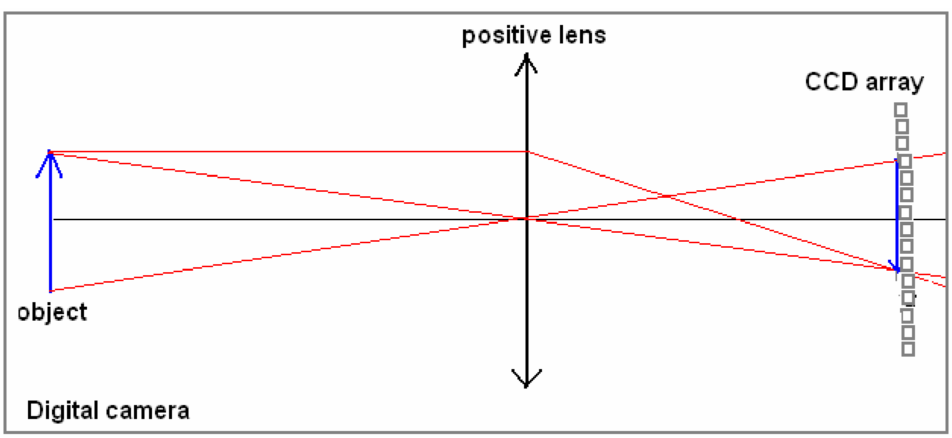
Some pros and cons of film cameras are listed below.

Advantages	Disadvantages
Better resolution	Limited depth of field
Ability to focus	Aberrations
One "negative" can make infinite "positives"	Expensive!
	Post processing - Negative has to be developed

1.4 Digital Camera

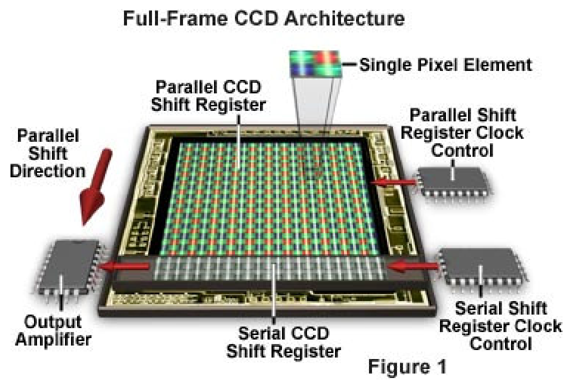
- Replace film with "electronic pixel arrays" (like CCD) with a fairly linear response to the incident light intensity.

- Make sure that the psf width of the imaging system is greater than a single pixel width to avoid aliasing.



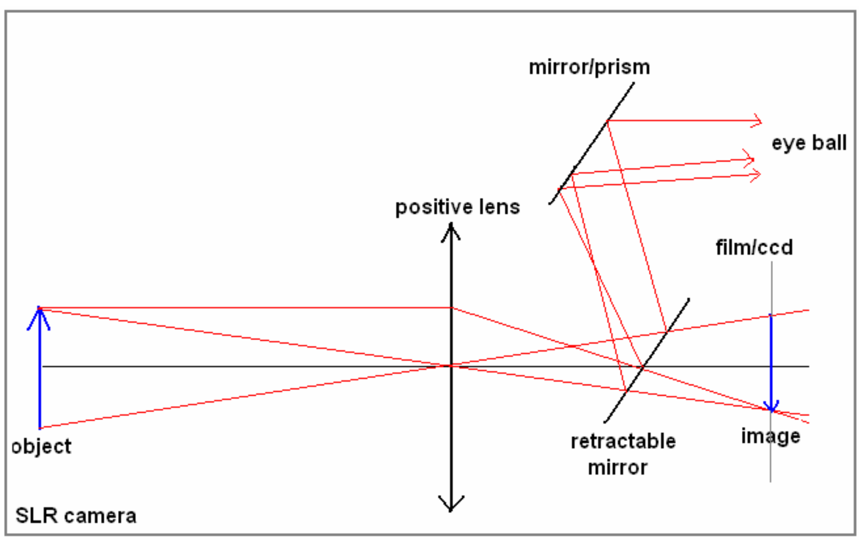
- This gets rid of the "grain noise" in film, but introduces new types of noise like quantum read noise, etc.

- The main advantage is that there's no time/effort spent on "development". Since the information is digitized, it can be readily transferred to a digital computer, could be processed (image processing) and printed, if necessary.



1.5 SLR camera

- SLR (Single Lens Reflex) cameras were invented in order to get rid of the imaging inaccuracy caused by the fact that in non-SLR cameras, the photographer sees through the "view finder" while the camera "sees" though the lens system. Hence, in non-SLR cameras, strictly speaking, the image is not exactly what the photographer wanted! (But, it's very close, up to a transverse displacement error)



- In a SLR camera, the "viewfinder" is eliminated, and so, both the photographer and the camera "see" through the lens system. *What you see is what you get!*

- Normally, the retractable mirror is in the position as shown in the above picture. When the camera is "clicked", the retractable mirror moves upward so that the rays get imaged on the detector.

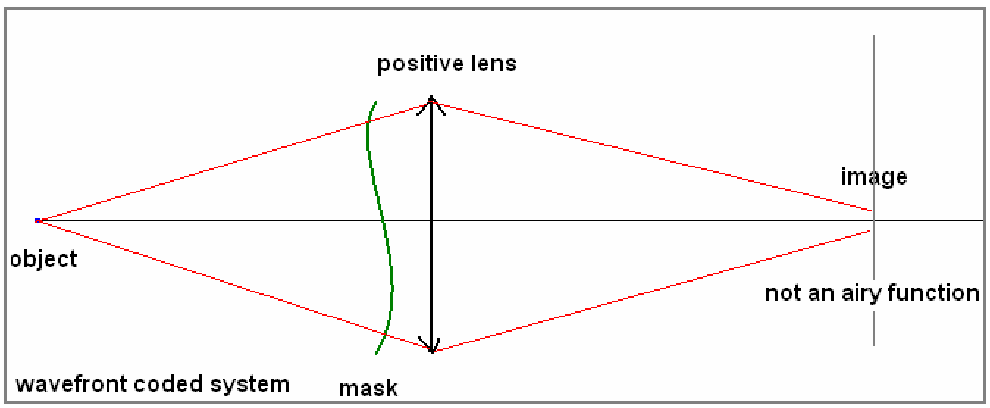
- All this makes sense only in cameras that do not have a "LCD" display screen. These days, most contemporary cameras have real time digital displays showing exactly what is seen by the camera. The user is not forced to see though the viewfinder, and so, perhaps, the future of SLR cameras is at stake!

- Typically, these cameras are bulky because of the additional retractable mirror and the mechanical system required to drive it.

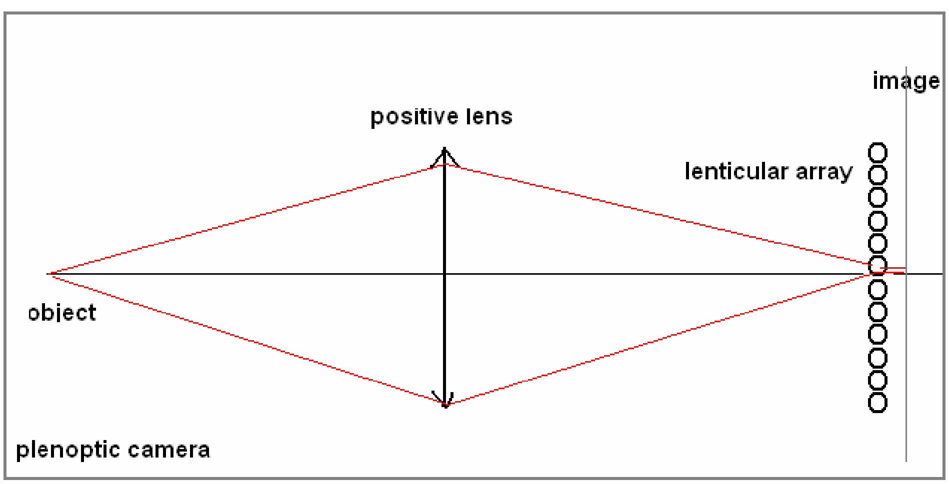
A Kodak SLR Camera

1.6 Passive 3D Cameras

- 3D cameras capture both range (z) and transverse (x/y) image profiles.
- Examples include plenoptic camera and Wavefront coded cameras



- Plenoptic camera uses lenticular arrays before the detector plane, while wavefront coded cameras use special amplitude/phase masks in the pupil plane. Both of these systems require some post processing to retrieve the actual 3D information.



- Piestun Group's[4] 3D camera uses diffractive holographic optics for 3D imaging.

1.7 Where are we heading?

For a long time, one of the strong goals in camera design was to design a high resolution, cost effective, aberration less, extended depth, high field of view, fast (low F/#) cameras. In the last few centauries, we seem to have understood that simultaneously satisfying all of these requirements is impossible, as there are some fundamental limits (like NA vs DOF) involved. A clear understanding of these limits certainly is a sign of maturity, because it's extremely important for an engineer to know not only what he can do, but also what he cannot do.

Stanford's Ren Ng with his 3D camera

So, is that it? Isn't there anything more that can be done? Historically, the answer for such questions has always been "No! There's more!!" Progress in the development of night vision cameras indicate that there's a lot of interest in making these optical designs work in other regions of the EM spectrum. Progress in 3D cameras (a relatively immature field!) indicates that cameras can see something "more" (in this case, range) than transverse images. Camera designs seem to be progressing towards capturing something that's hidden in the images produced by conventional cameras. "Target specific cameras", which could essentially identify features in objects "optically", could be yet another field to explore.

-------------------- End of part 1 ---------------------------

2. Contemporary digital camera design

The goal of this part is to create an aberration corrected, zoom enabled, digital camera for imaging objects a distance greater than a few meters. (Infinity! in optics lingo).

The specifications are listed below.

Specifications	
Parameter	**Value**
Object location	infinity
CCD resolution	10 u per pixel 6 mega pixels
CCD dimension	3cm x 2cm
Color filter	RGB
Size	~10cm x 10cm x 12cm (max zoom)
Weight	300g
Cost	$400
Optical Zoom	5x
Digital Zoom (interpolate)	4x
Aberration corrected	Yes
LCD	2.5”
LCD pixels	230,000
FOV	Varies with zoom
EM regime	Visible

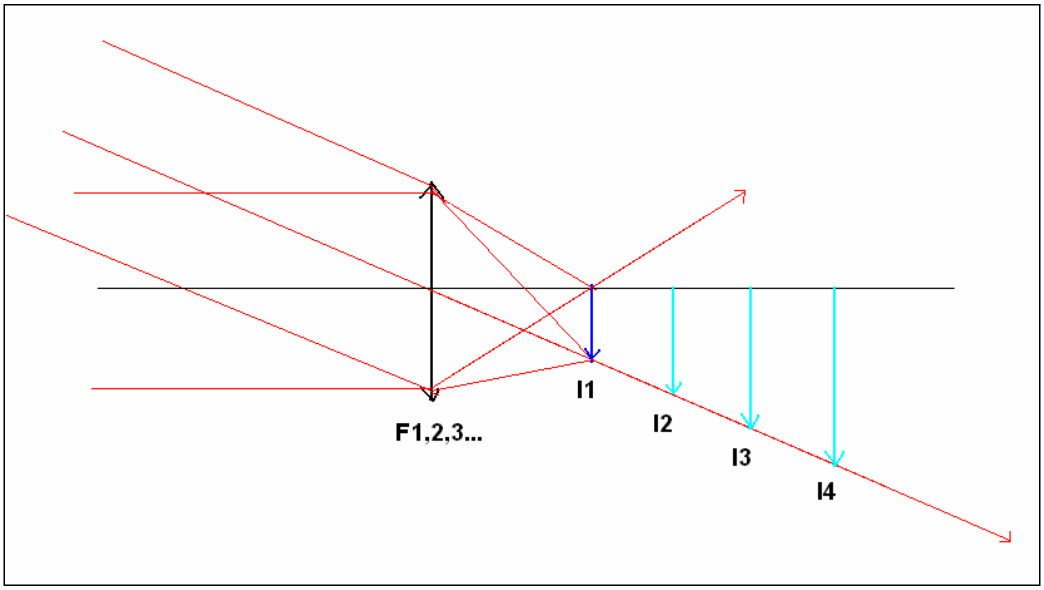
A realistic camera would typically have many more specifications such as image processing, networking, battery power efficiency, self-timer, remote control, and so on. But, for the purposes of this “Optical System Design” project, these “details” can probably be ignored with impunity.

2.1Ray sketches

In this section, many possible ways of designing a zoom enabled camera will be explored. Thin paraxial lenses will be used, and (hence) aberrations will not be dealt with. We are now in the idealized aberration free world of optics. The goal here is to skim through different possibilities, and to pick the one that suits our specifications. Once this is done, the next section on paraxial design would rigorously analyze the chosen design analytically with appropriate numerical data.

Zoom lenses are often confused with varifocal[5] lenses, which are lenses having variable effective focal length, but in these lenses, the detected image need not necessarily be in focus. In contrast, zoom lenses remain perfectly in focus while their effective focal length is changed. The difference is subtle. This can be achieved by either by mechanical compensation (mechanical systems that physically displace appropriate lenses axially) or by optical compensation. Typically, a zoom lens design is called optically compensated, if the system remains in focus for three or more different focal lengths in the zoom range. Note that in all other intermediate regions, an optically compensated zoom lens suffers from slight defocus.

Let's start with a single positive lens and analyze if we can build our camera with it. Assume that this lens is imaging an object at infinity, as shown below. As the power of the lens is decreased, the image plane is pushed farther behind the lens. More importantly, the magnification is increased! In this example F1 < F2 < F3 < … and consequently I1 < I2 < I3 < …



This basic principle is sufficient for designing a zoom lens. [We'll tackle aberration less design a little later!]. For zooming in on an object, all we have to do is to reduce the focal length of the system and also simultaneously increase the distance between the image plane (detector) and the lens. We now need to come up with a system whose focal length can be varied dynamically.

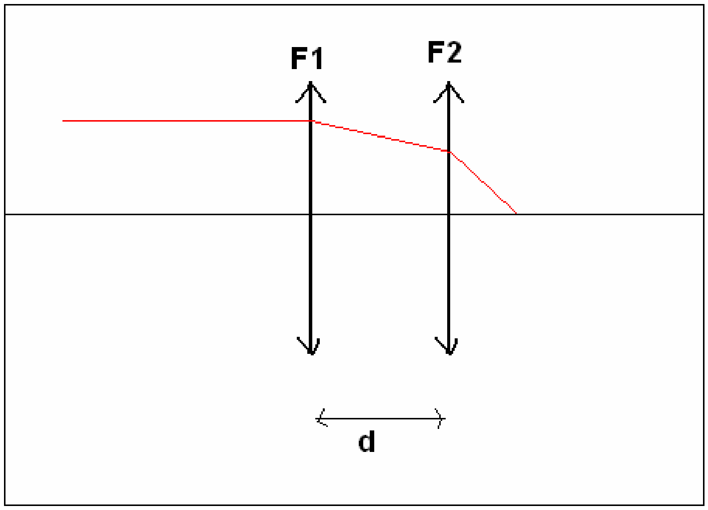
The focal length of a single lens in air gives us about three degrees of freedom – refractive index and two curvatures (n, c1, c2). Forget thickness, we aren't dealing with thick lenses yet. But, once manufactured n, c1, and c2 are fixed, and so, for a given wavelength, and a given external medium, there's no way that we can vary a lens's focal length.

$$\Phi = (n-1)(c1 - c2)$$

The only possible way seems to be to use multi element lenses. The effective power of two lenses separated by a distance **d** is described by the following equation:

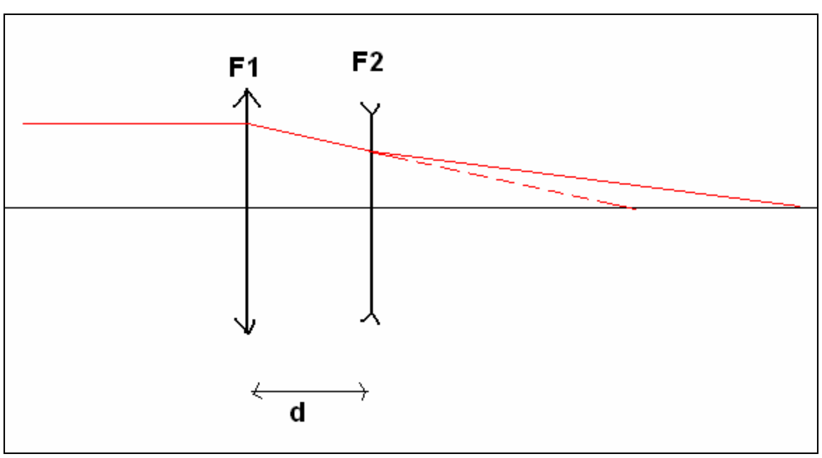
$$\Phi = \Phi_1 + \Phi_2 - d\Phi_1\Phi_2$$

For two positive lenses separated by **d**, effective power decreases as **d** is increased. Note that the, the principal plane locations also vary as **d** is varied. For keeping the image in focus through out the zooming range, we should also change the locations of F1, F2 relative to the image plane.



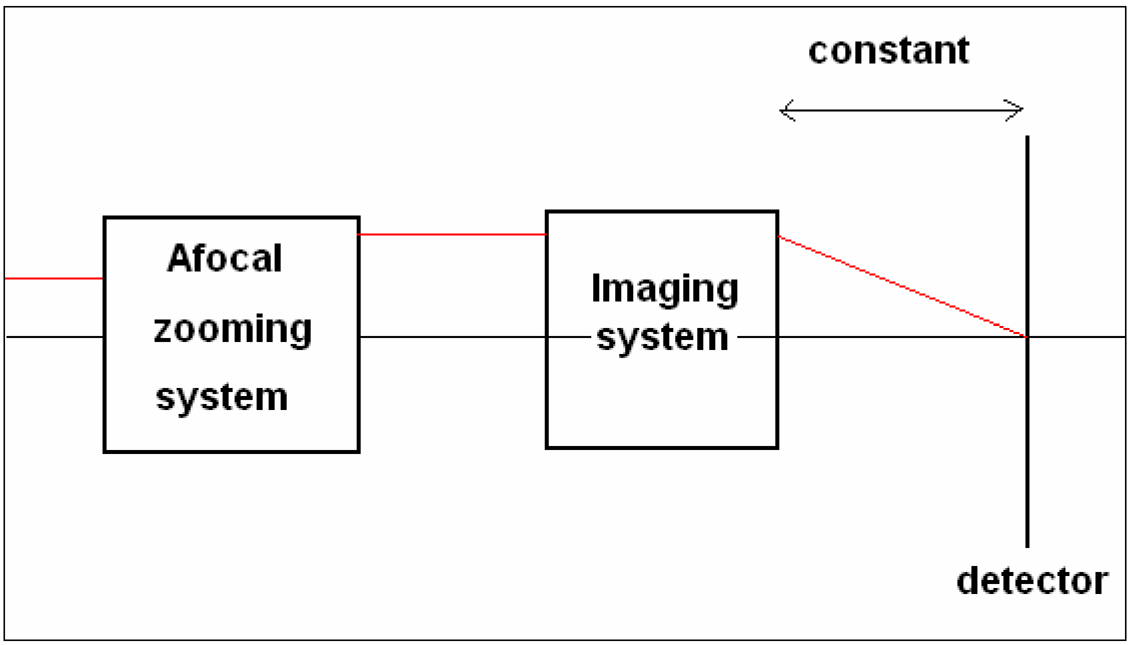
Hence, there is a need for two separate mechanical systems. The first one is for changing **d** so as to change the effective power, and the second one is for changing the location of F1, F2 with respect to the detector plane. Since the detector plane is typically fixed, the two lenses should be pushed forward (away from the detector) for zooming in/out, depending on the lenses. Note that these two mechanical systems are not independent. The distance through which the two lenses should be moved relative to the detector is a function of **d**. All this is to say that having smart optics isn't just enough; for zooming to work properly, we need to have smart mechanical motions system too.

Note that the same can also be implemented with one positive and one negative lens as shown below



But, in this case, since F2 is negative, the effective power and **d** bear a different relationship. Specifically, as d increases, the power also increases! This system seems to have some advantages over the two positive lens system, as it can potentially eliminate some off axis aberrations. The total petzval curvature can be made zero, leading to higher unaberrated field angles. But, lets not worry much about aberrations at this point.

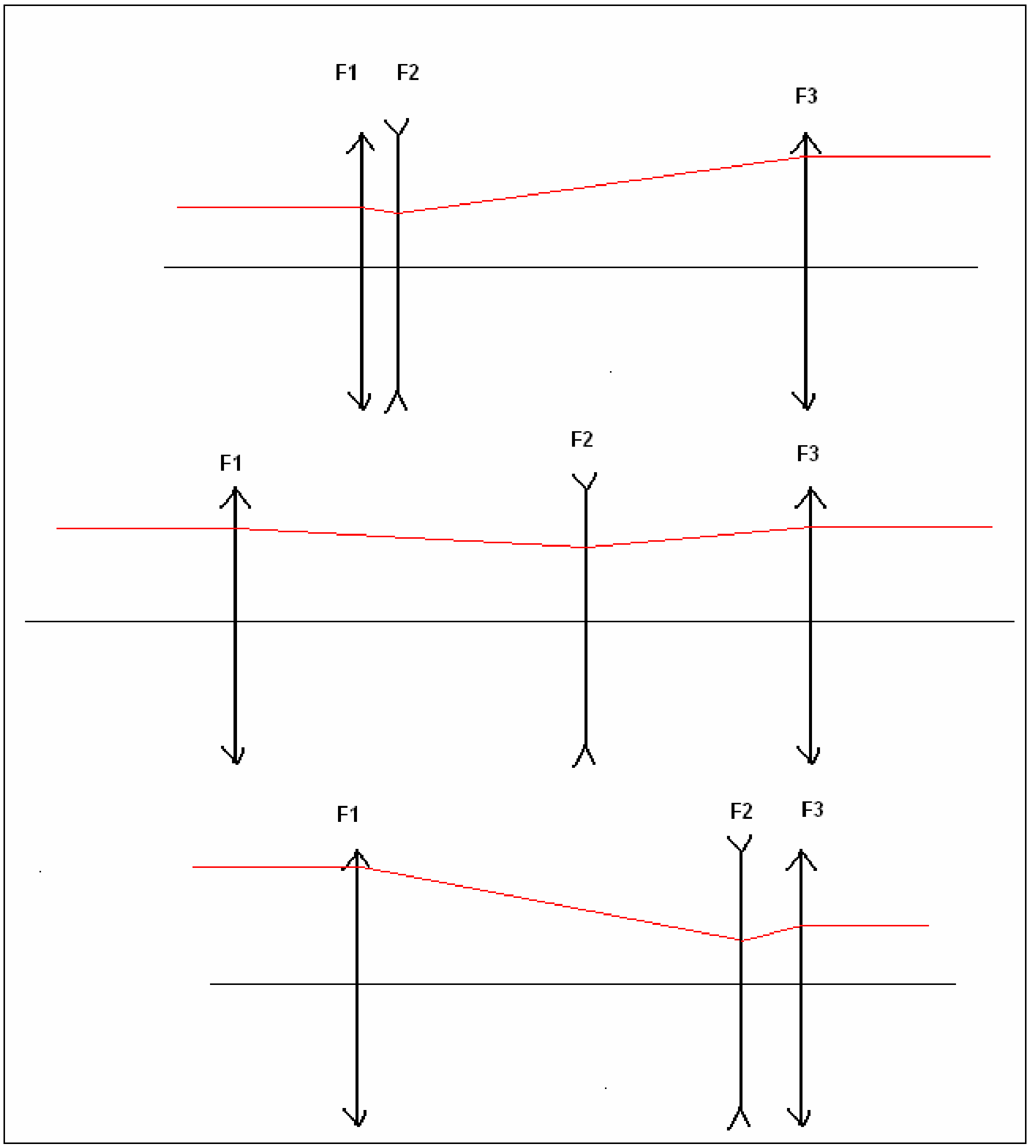
In the above basic zoom systems, we are using the same set of lenses for both zooming and for imaging. Another possible way is to divide the job of zooming and imaging, and employ different systems for them. One popular technique is the afocal zoom system, that always takes in and gives out plane waves (parallel rays! in geometric optics). The second sytem images these parallel rays on to a detector. One obvious advantage of such a system is that the image plane is always a constant with respect to the second imaging system. For any zoom, the image plane is always at the same location. Another advantage could be that the zooming system could be made detachable. The system would work perfectly even without the additional pluggable zooming unit.



The imaging system is simple! The bare minimum could be a single positive lens, and the image plane is always at a distance f, from the principal plane of the imaging lens. Of course, a single positive lens could be the worst possible lens for an aberrationless design; but again, let's not worry about aberrations yet. After getting the basic components right, we could narrow down on each lens of the system and correct aberrations.

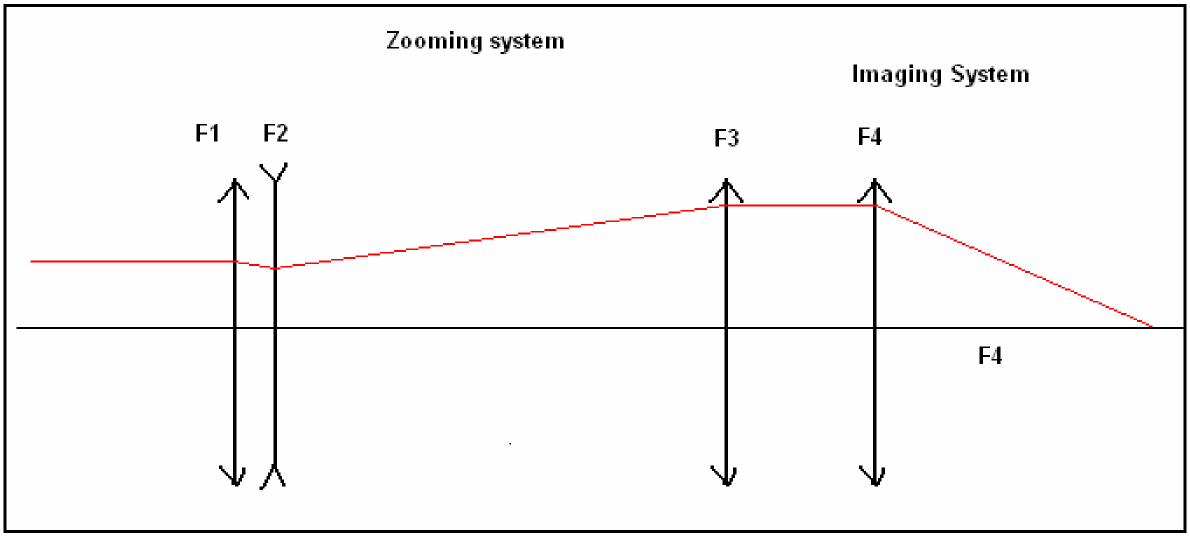
The design of an afocal zooming system needs more thought, but, looks like many have thought about it before (not surprising!), and many elegant designs have been widely published. One such afocal zoom lens design is discussed in *Malacara, Handbook of optical design*. The system basically has a negative lens between two positive lenses. Variable zoom is obtained by moving the negative lens relative to the positive lenses. When the negative lens is at extreme positions (close to F1 or F3), the system is perfectly afocal. On the other hand, when the negative lens is some where in the middle, then the system as such is not afocal. In order to make it afocal, the position of the front lens F1 should be adjusted (mechanical compensation).

The distance between the two outer most positive lenses is essentially a function of the position of the negative lens. Hence, we need two mechanical systems again – one for translating the negative lens for changing the angular magnification, and the other for varying the distance between the two outermost positive lenses so as to keep the final output rays (of the afocal system) parallel.



Since we are still in the “Ray sketch” part, at this point, we do not bother about the actual values of the focal lengths, expressions, distances, etc. As noted before, the goal at this point is to just have a quick look at different designs and to pick the best. Later, in the paraxial design part, we’ll come up with analytical expressions for the chosen ray sketch, and start the actual design procedure.

Sticking the zooming and the imaging systems together, the total system looks like the following.



The above system seems to be good for the following two reasons

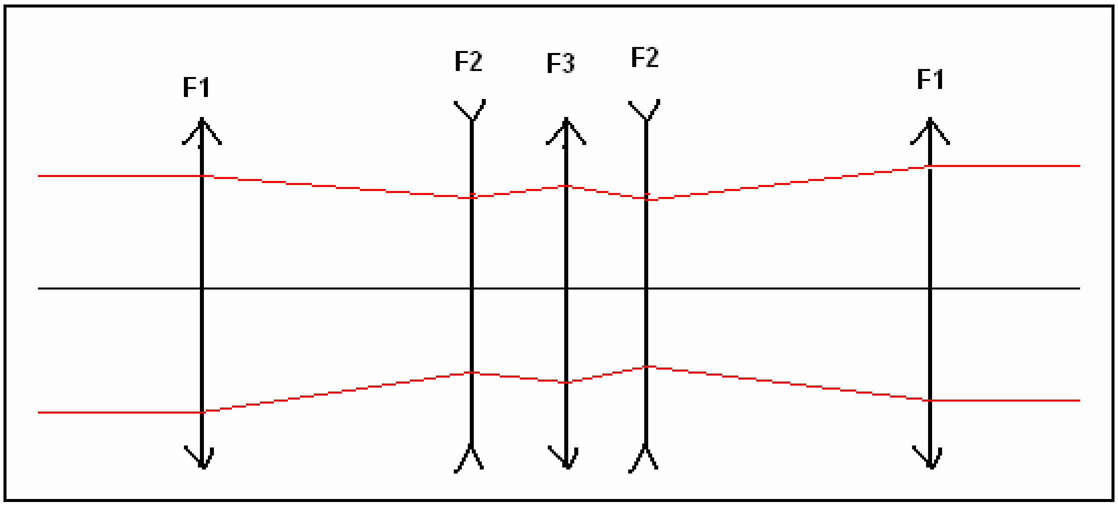
1. Simple, yet serves the purpose elegantly.

2. The idea of having a detachable zooming system is attractive. Looking from the marketing perspective, Zooming systems are always expensive (not only because of the optics, but also because of the mechanical systems involved), and so we might lose potential customers who can't afford much. But, with a detachable zoom, the marketing could possibly argue "buy the basic imaging system now at a very cheap price, and Zoom lens can be purchased separately if required". Much similar to Apple's IPOD strategy; There are so many optional IPOD accessories that aren't absolutely necessary for the IPOD to work.

The above design clearly needs mechanical compensation in order to keep the image in focus. In other words, for every small movement of the negative lens F2, the front lens F1 has to be moved relative to the back lens F3 to keep the system afocal, and hence to keep the detected image in focus.

The compensation can be made optical by replacing the central negative lens with a combination of three lenses (a positive lens in between two negative lenses). The central positive lens is stationary, while the negative lenses have to be moved to create variable zoom. As before, when the negative lenses are at their extremes, the system is perfectly afocal. As the negative lenses are moved from their extreme positions, the afocal condition is violated! This problem can be solved more elegantly (instead of displacing other lenses) by taking advantage of the central positive lens, which essentially is an additional degree of freedom in this system.

For instance, consider that the variable zoom lens gives a magnification range of [M1, M3], where M3 > M1. Clearly, the system is afocal (and hence in focus) when the magnification is M1 or M3. The focal length of the central positive lens can be chosen such that the zooming system is afocal at some M2, that's exactly inbetween M1 and M3. Say, M2 = 0.5 * (M1 + M3). Now, the system is perfectly in focal for three equally spaced magnifications in the entire zoom range. As the negative lenses are displaced from their extreme positions (Magnification = M1) , the defocus would increase form zero, reach a maximum, and fall down to zero again when the magnification is M2. As the negative lenses are displaced further (in the same direction), the misfocus increases again until it drops to zero precisely when the magnification is M3. Clearly, the introduction of three new lenses would reduce the maximum amount of misfocus as the zoom is varied by displacing the negative lens alone. (no other mechanical compensation). If this misfocus is tolerable for the application under consideration, then the system is said to be optically compensated.



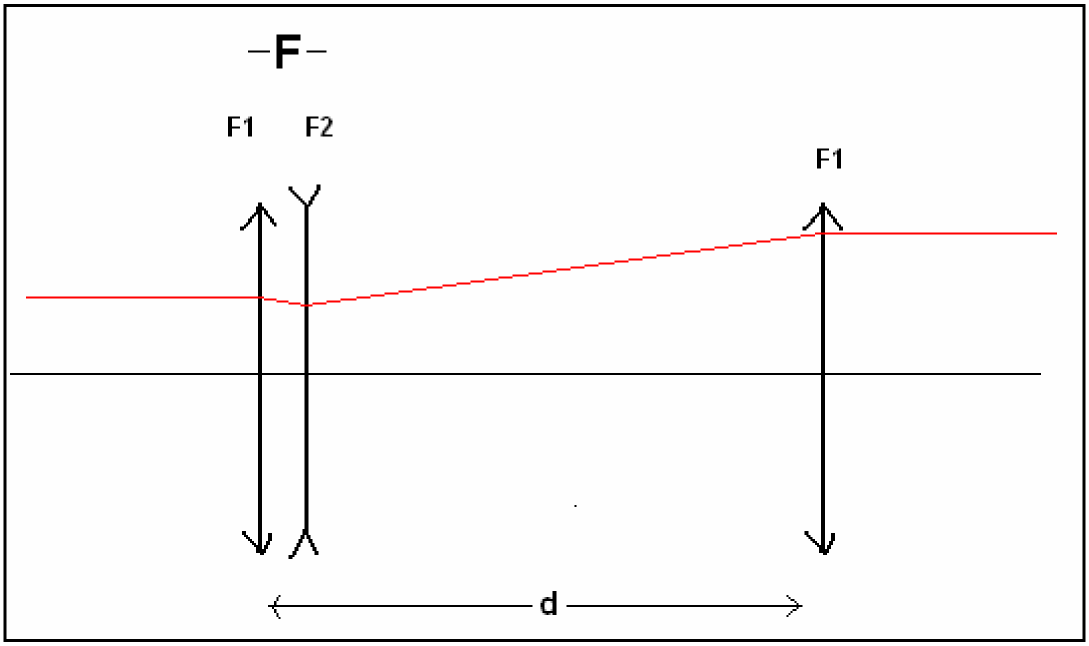
Alright, that was a fancy optical compensation theory. But, let's now analyze if this is really what we want. Clearly, optical compensation takes away the need for an additional mechanical system (good!). Static systems are always more robust than mechanical systems. Ideally we'd want to design a zoom system without any mechanical motion at all. But, from the above discussions, it's hopefully clear that it's impossible to design a stationary zoom system (unless, one can dynamically change the refractive indices or curvatures of lenses!), and so, it's definitely nice that optical compensation helps us in getting rid of one of the two mechanical compensation systems. But, there's no free lunch! The side effect is that it introduces misfocus (in the paraxial world!) in all zoom positions except for three. Misfocus widens the psf of the system, and hence the resolution decreases. Also, we need to introduce two additional lenses ($$ -- as this is a "visible light" camera, we need acromats). Further, the weight of the system would increase! (This is supposed to be a hand held camera – lighter the better)

It's time for a decision! Stationary, heavy, more expensive zoom design that could potentially hurt the resolution of the system **or** Light, less expensive, high resolution, mechanically compensated system? Yes, you guessed it right (?)! The author opts for the latter!

Now, we have the basic ray sketch diagram. We can now go ahead and do a more detailed/careful paraxial design analysis.

2.2 Paraxial Design

This section will be entirely based on the final ray sketch chosen in the previous section. Here, we'll be analyzing the system in detail by deriving expressions for important parameters like magnification, focal lengths, distances, etc. Since many of these parameters are interdependent, varying a parameter will almost certainly affect another. Therefore, it is important to come up with plots of interdependent variables. Such plots are extremely helpful not only to come up with an optimal design, but also to convince the client that what we designed is indeed optimal. Developing such a design is the primary goal of this section. Needless to say, since we are still in the "paraxial" world, aberrations will be ignored.



Consider the "chosen" ray sketch. The two positive lenses are separated by a distance **d.** In the configuration shown above, the negative lens is "actually" sticking on to F1. In other words, the negative lens is in its left extreme position. In this configuration, the distance **d** and the focal lengths **F1, F2** should be chosen such that the zooming lens system is afocal.

We will now derive analytical expressions for **F1** and **F2** as functions of the distance of separation **d** and the magnification of the system. These derivations are inspired from Malacara's classic section on varifocal lenses, although, the author believes that the derivation in Malacara is more abstract that what is done below.

Define **F** as the effective focal length of **F1** and **F2,** when their distance of separation is essentially zero (above configuration)

$$\frac{1}{F} = \frac{1}{F1} + \frac{1}{\mathrm{F2}}$$

$$F = \frac{F1F2}{F1 + F2}$$

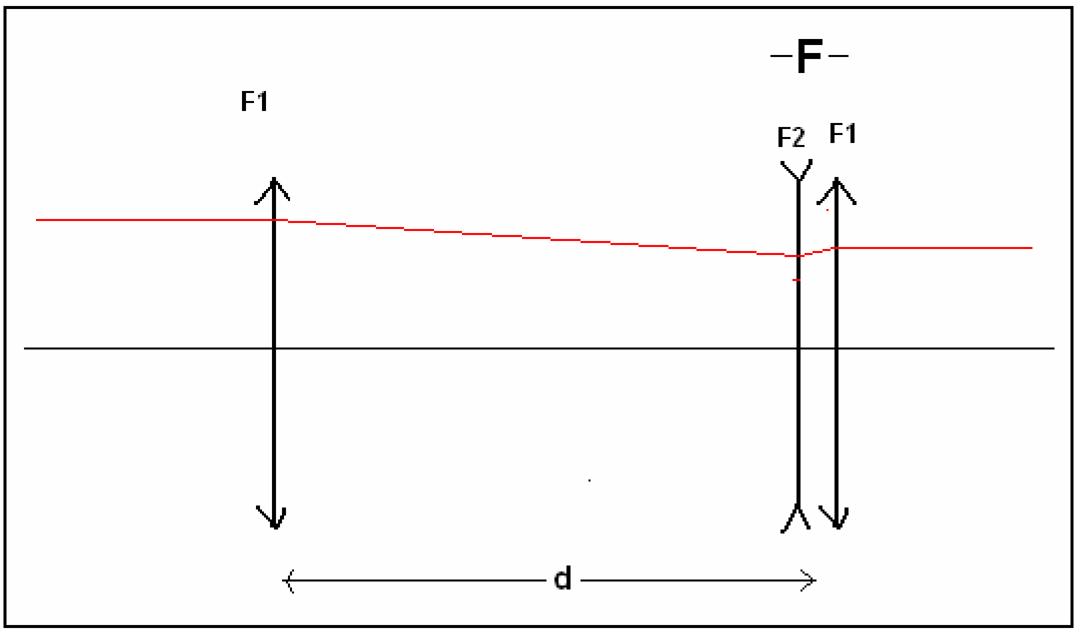
The negative lens is chosen such that it's power is greater than twice the power of the positive lenses. In other words, in the above configuration, **F** is negative. So, what we have in front of us is an afocal system with a front "effective" negative lens **F** and a back positive lens **F1**. This is nothing but a basic Galilean telescope.

$$M1 = -\frac{F}{F1}$$

Magnification (**M1**) is the negative ratio of the focal lengths. The "1" in **M1** indicates that this is valid only for this particular extreme position 1. Let's now analyze M1. Since the negative lens is much more powerful than the positive lens, **F** is negative. Implies, **M1** is positive. Again, since the magnitude of the power of the negative lens is over twice that of the positive lens, the focal length of the positive lens is longer!

Implies, **0 < M1 < 1**

Therefore, in this orientation, the zoom system produces a minified image. Now consider the other extreme orientation, where the negative lens is in contact with the second positive lens (in the right) as shown below.



The value of **F** remains the same as the two positive lenses have identical focal lengths. Again, this is an afocal Galilean telescope. But, this time the telescope is made of a front positive lens and a back negative lens.

The magnification, as before, is given by the negative ratio of the focal lengths

$$M2 = -\frac{F1}{F}$$

$$M2 = \frac{1}{M1}$$

Since we already proved that **0 < M1 < 1** , clearly

M2 > 1

M1 and **M2** define the zoom range of the system. That said, it's important to understand that **M1** and **M2** are only the limits – Theoretically, any value of zoom between **M1** and **M2** can be achieved by moving the negative lens **F2** between the two extremes. We are only constrained by the precision with which the negative lens can be displaced.

Since the system is afocal in both of the above configurations,

d = F + F1

F = d – F1

From the expression for **M1**

$$F1 = \frac{F1 - d}{M1}$$

$$F1 = \frac{d}{1 - M1}$$

Since $F = \frac{F1F2}{F1 + F2}$

$$F2 = \frac{F\,F1}{F1 - F} = \frac{F1(d - F1)}{F1 - (d - F1)} = \frac{F1(d - F1)}{2F1 - d} = \frac{\frac{d}{1-M1}(d - \frac{d}{1-M1})}{\frac{2d}{1-M1} - d}$$

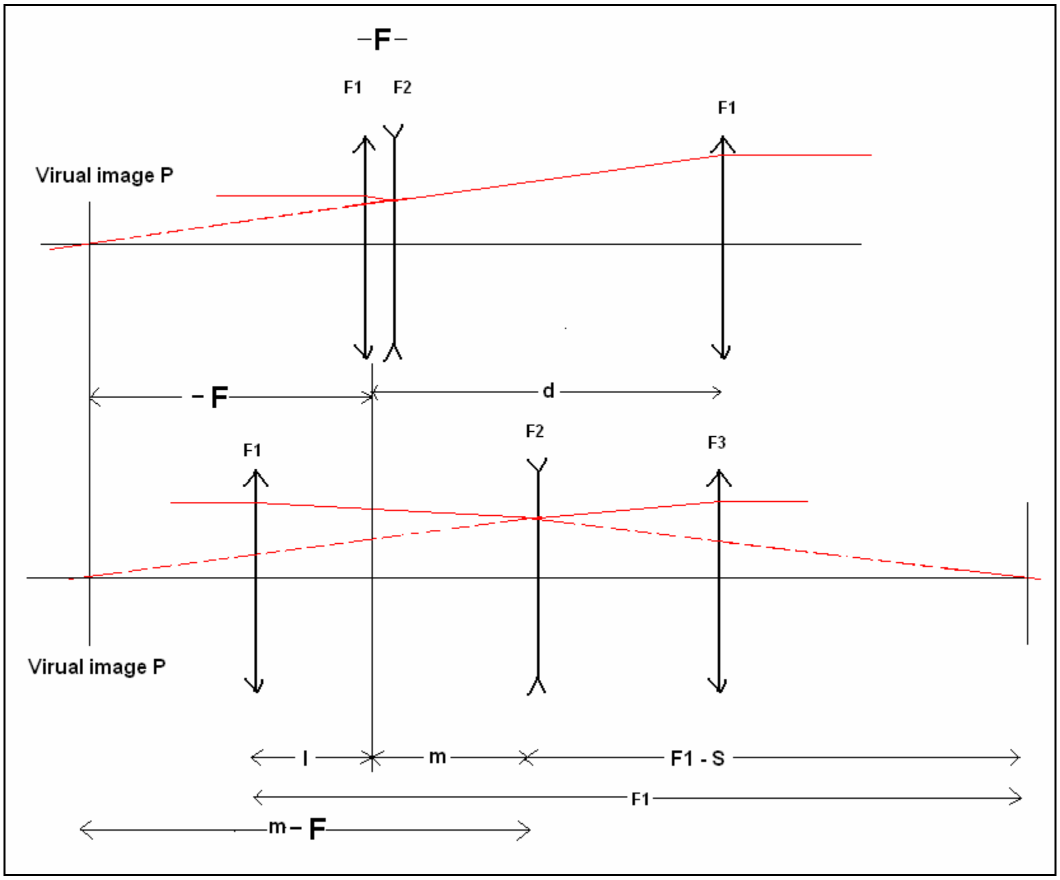
$$F2 = -\frac{M1d}{1 - M1^2}$$

As noted earlier, this system requires mechanical compensation to retain the afocal condition when the negative lens is not in its extreme positions. Typically, this mechanical compensation is achieved by displacing the front positive lens with respect to the back positive lens. That said, it is important to precisely know the distance through which the front positive lens should be displaced corresponding to the change in location of the negative lens. We will now be deriving analytical expressions for nailing down the key parameters of the required mechanical compensation.

For every small displacement **m** of the negative lens, assume that the front positive lens should be moved by a distance **l** in order to maintain the system in focus. [See figure below] These two movements have to be done simultaneously maintaining the virtual image **P** at a fixed position in space.

The middle and the front lenses are separated by **S**

S = m – l   Note: **l** < 0



Writing the thin lens equation for middle negative lens, we have

$$\frac{1}{F2} = \frac{1}{F-m} - \frac{1}{F1-S}$$

Substituting the definitions for S and F,

$$\frac{1}{F2} = \frac{1}{F-m} - \frac{1}{F1-m+l}$$

$$F1-m+l = \frac{(F-m)F2}{F-m-F2}$$

$$l = \frac{(\frac{F1F2}{F1+F2} - m)F2}{\frac{F1F2}{F1+F2} - m - F2} + m - F1$$

$$l = m(1 - \frac{(F1-F2)^2}{F1^2 + (F1+F2)m})$$

Writing in terms of $M1$

$$l = m(1 - \frac{d}{M1^2 d + (1-M1^2)m})$$

The above relation is important. It relates **l** and **m** directly. All other parameters in the expression are constants. So, for a given displacement of the negative lens (**m**), we can now precisely determine the distance through which the front positive lens should be moved (**l**).

The magnification of the lens at any position of the negative lens is given by

$$M = \frac{M1d}{d + (l-m)(1-M1^2)}$$

This relation is important too. **M** is typically displayed on the LCD screen of a digital camera as the zoom is being varied.

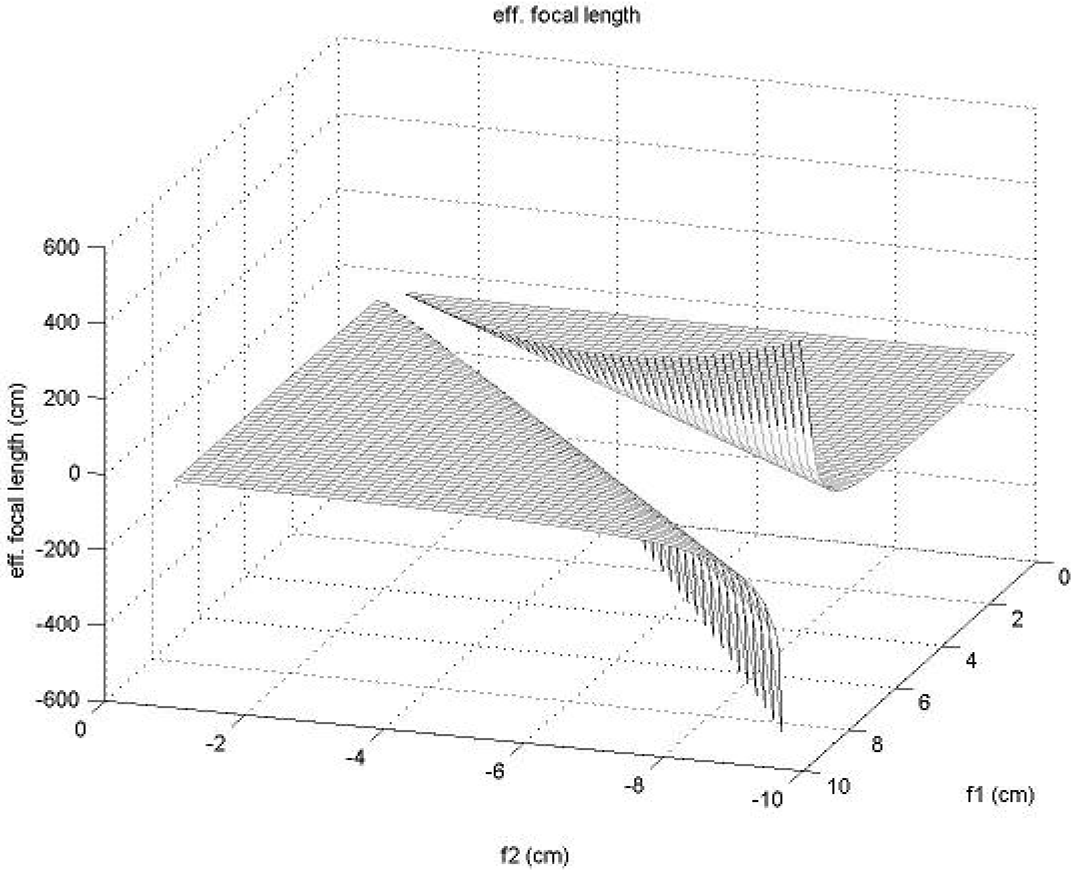
Now that the paraxial system in hand is analytically characterized, it's time for plugging in some values for lenses and distances.

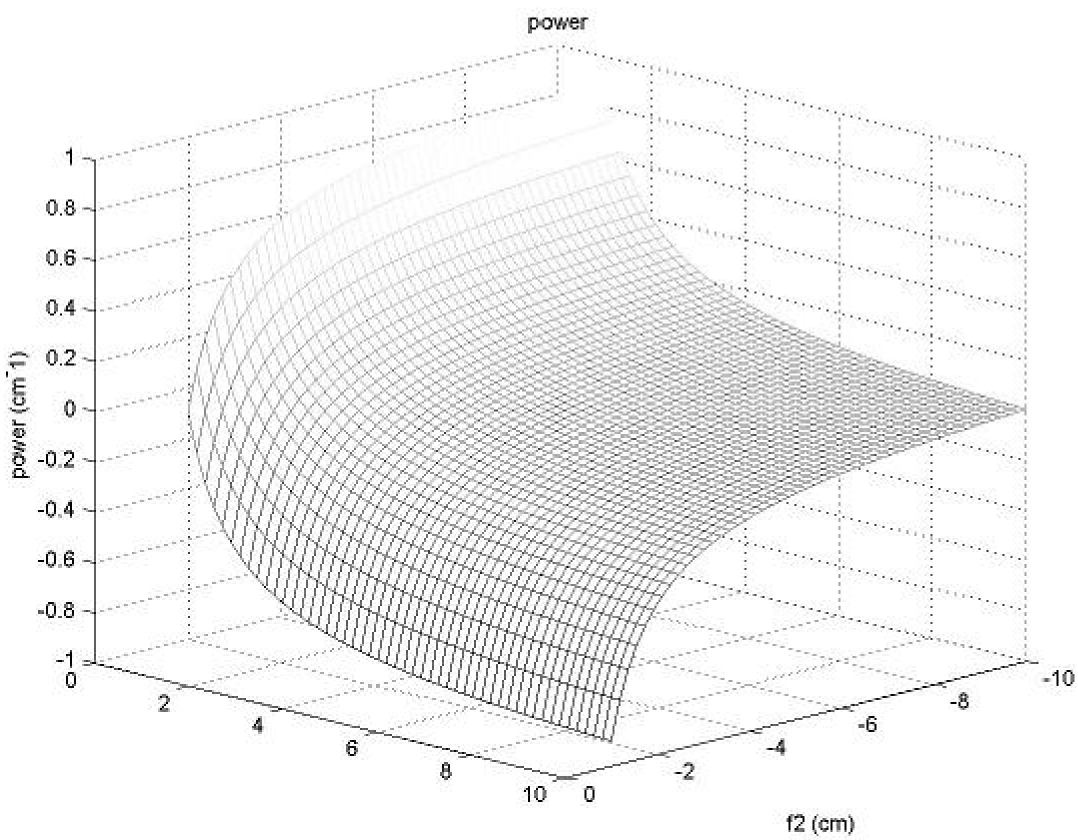
While doing this, we'll have to remember the specifications:

1. The system should be reasonably compact
2. Not too expensive

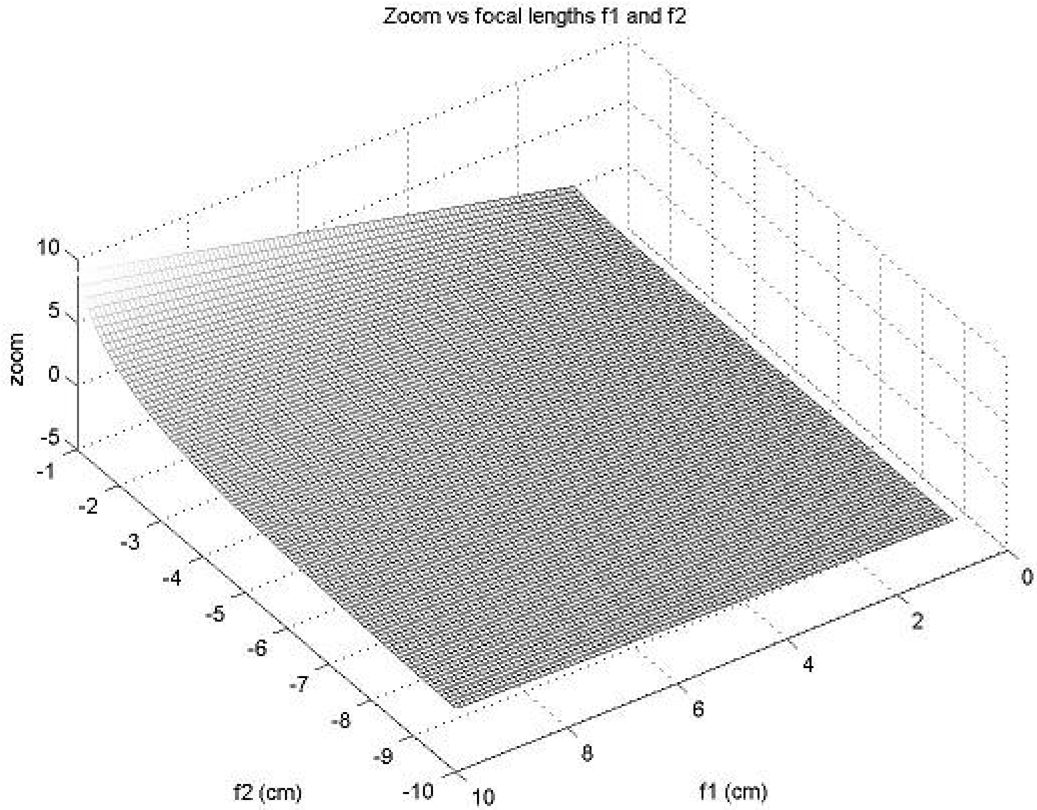
We now rigorously analyze various parameters like throw, zoom, cost, etc as functions of available degrees of freedom. F1, F2, F3, F4, and d are the variables shown in the paraxial ray sketch. But these parameters are not independent. For example, d depends on the focal lengths inorder to maintain the afocal condition. We have already assumed F1 = F3 in the above analytical analysis. Hence, F1, F2, and F4 are the true degrees of freedom. Of these three, F1 and F2 are important as they characterize the zoom lens.

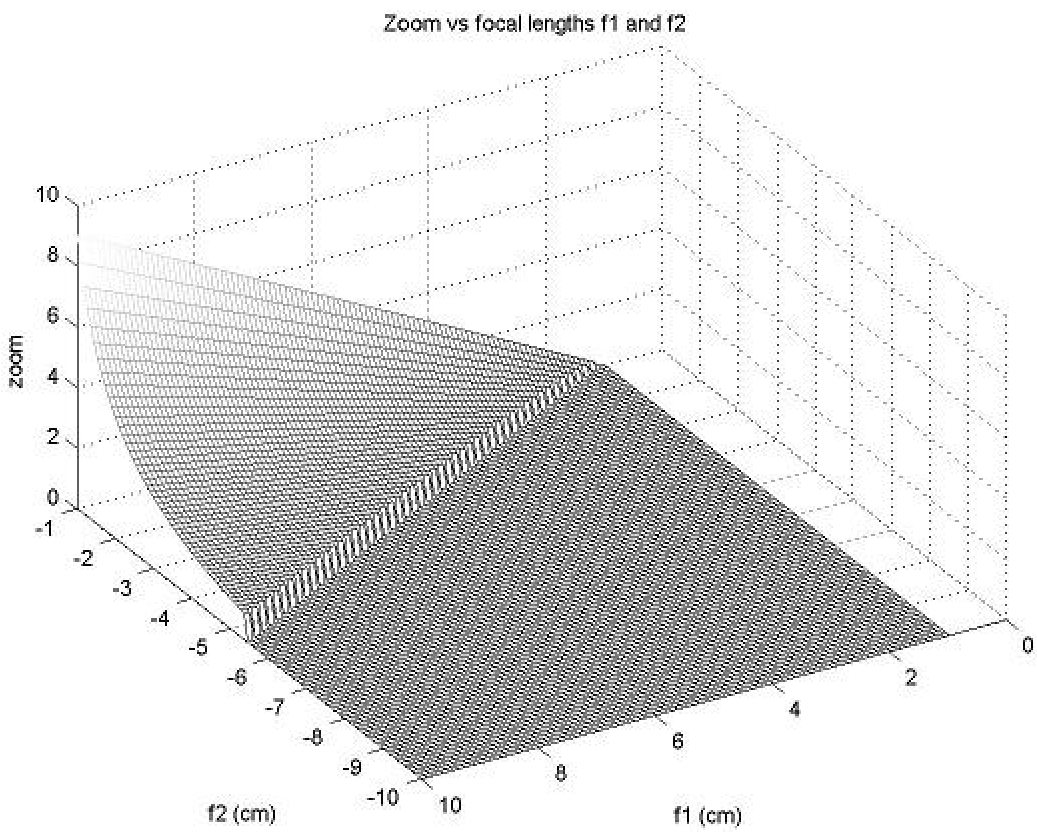
Design analysis 1



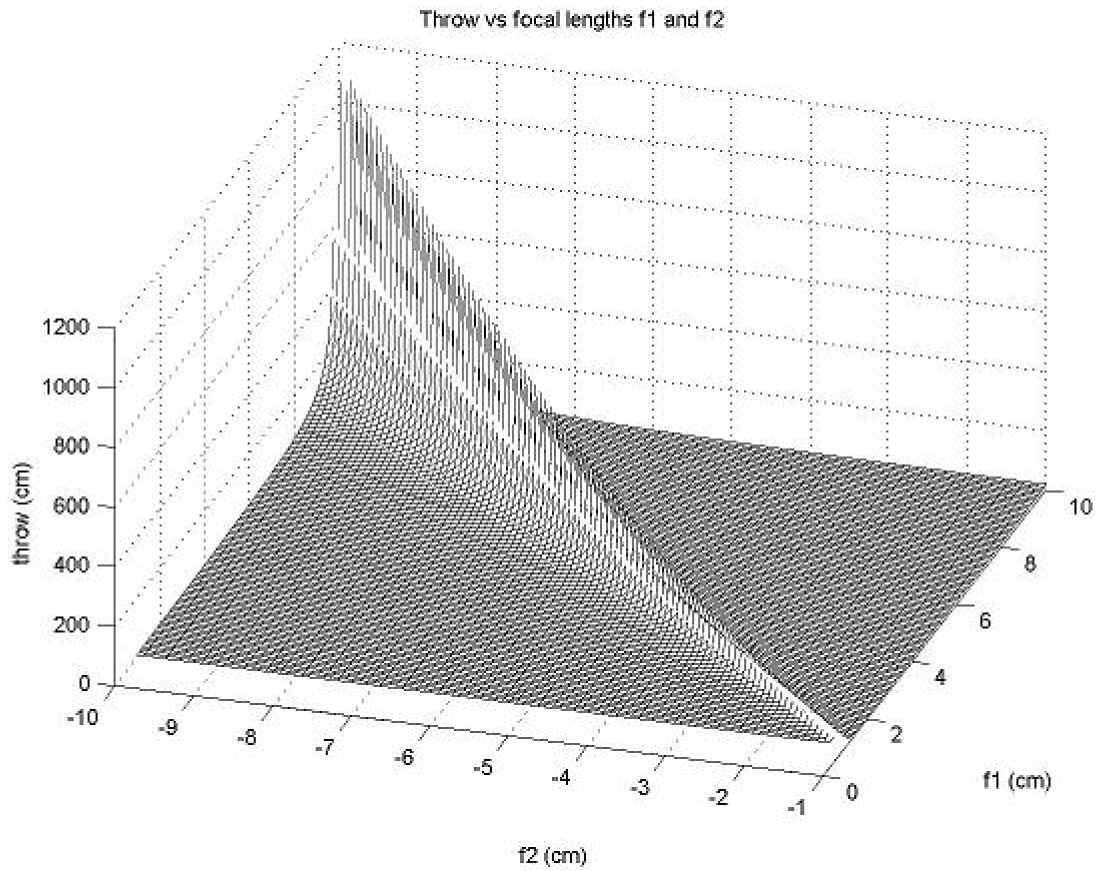


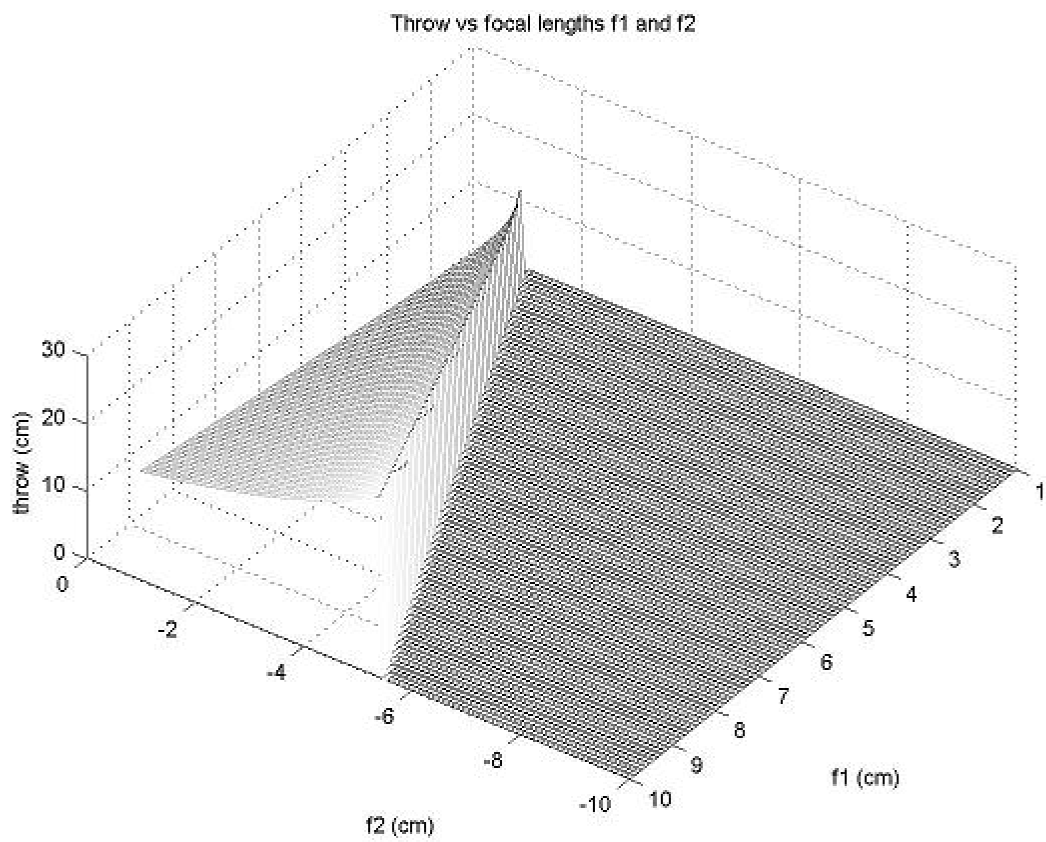
Design analysis 2





Design analysis 3





In "Design analysis 1", we show the effective focal length of two lenses (one positive and the other negative, just as in the two extreme zoom lens positions) close to each other, as functions of f1 and f2. In the second plot, the power (inverse of effective focal length) is shown. Clearly, the effective focal length tends to infinity (power tends to 0) as the magnitudes of f1 + f2 tends to 0. (Note: f2 < 0)

"Design analysis 2" illustrates the dependence of zoom on the two focal lengths. The throw tends to infinity as the f1+f2 tends to 0. But, note that in our system, f1 and f2 cannot take arbitaty values! For the zoom lens to be afocal, the negative lens must be atleast twice as powerful as the positive lens. Implies, f2 < 0.5 * f1. The second plot applies this constraint.

"Design analysis 3" shows how the throw of the system varies as a function of f1 and f2. The total throw depends on f4 too! But, throw dependence on f4 is linear, and hence not interesting. In the 3D plots shown, we have assigned f4 = 6cm

From these three design plots, we get a clear idea of the interdependence of the focal lengths, throw, and zoom. For instance, zoom can be increased arbitrarily by increasing F1. But, increasing F1 will result in an increase in throw. Ideally, we'd want large zoom and small throw. Since, the best of both worlds cannot be picked simultaneously, we will have to choose an optimum value of both.

Our spec insists on ~5x zoom and ~12 cm throw. This can be achieved by choosing:

F1 = 8cm
F2 = -1.25cm
F4 = 6cm

Plugging these values in the earlier equations, we have

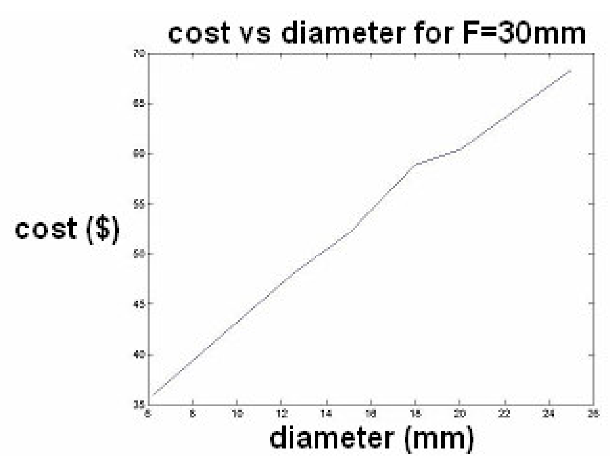
Effective focal length in extreme positions of zoom, F = -1.4815
Throw = 12.5185cm
Zoom = 5.4x

So, we have exceeded the specified throw by ~0.5cm. But, we have done well on the zoom!

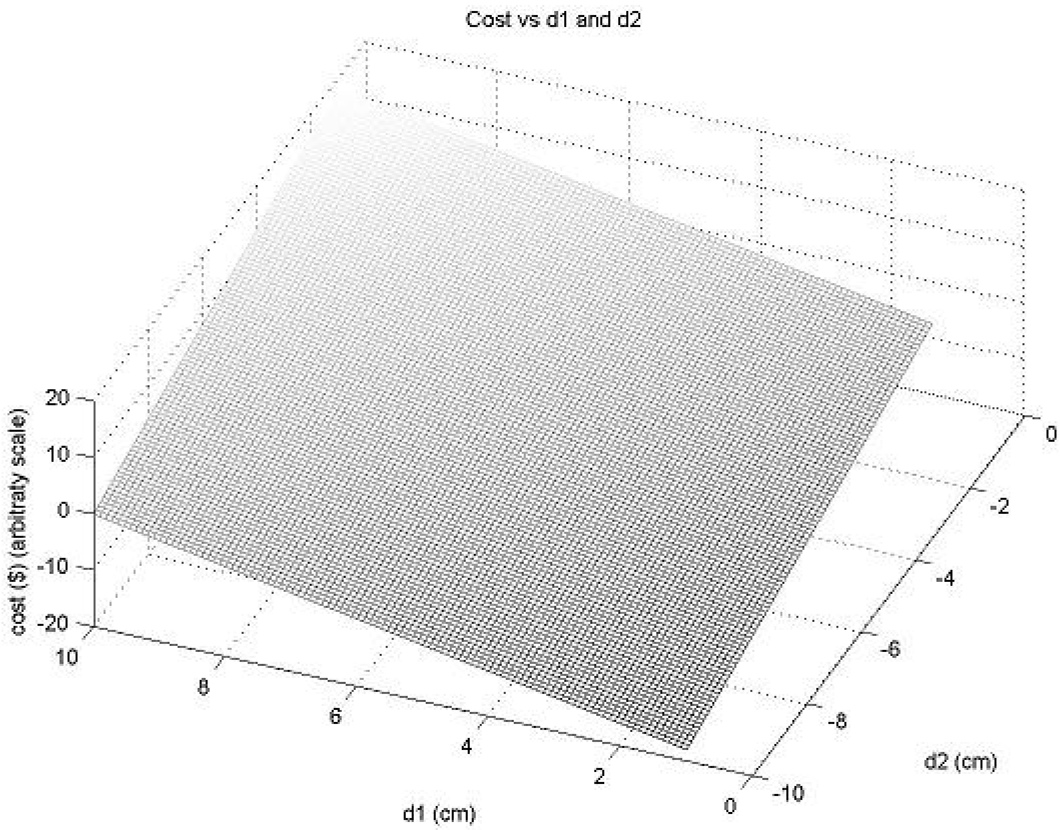
Now that we know the focal lengths, we can analyze the effect of varying the diameter of these lenses. In essence, vary the F/# and see the effect on cost. We'll be analyzing resolution, field of view, etc. once we complete the paraxial design.

From Edmund optics:

• LENS ACH 12.5 x 30 MgF2 TS RoHS	12.50	30.00	$48.00
• LENS ACH 15 x 30 MgF2 TS RoHS	15.00	30.00	$52.00
• LENS ACH 18 x 30 MgF2 TS RoHS	18.00	30.00	$58.90
• LENS ACH 20 x 30 MgF2 TS RoHS	20.00	30.00	$60.40
• LENS ACH 25 x 30 MgF2 TS RoHS	25.00	30.00	$68.30
• LENS ACH 6.25 x 30 MgF2 TS RoHS	6.25	30.00	$36.00



Almost linear!



Hence, lower F/# (higher resolution) can be achieved only with a higher cost. As F/# decreases, aberrations increase, and even here, there's a need to choose an optimum value of F/# so as not to shoot out of the budget while restricting the aberrations reasonably (more on this when we reach thick lenses) It is important to make sure that the diameter of F4 is same as F3 inorder to avoid vignetting. Note that lenses with large focal lengths can typically be made with large diameters. For our system, we do not want to go any faster than F/1 for two reasons.

1) F/1 optics are too expensive
2) F/1 means large aberration effects

Also, in order to avoid making custom lenses (expensive!), we need to make sure that these lenses are available in the market. Clearly, we would need achromatic lenses, as this camera is designed to work in the visible.

Edmund optics positive achromats: F1 = F3 = 8cm and F4 = 6cm D1 = D3 = 4cm D4 = 4cm

Description	Dia. (mm)	E.F.L. (mm)	Back F.L. (mm)	Glass Type	MTF Curve	Stock Number	Price *
▪ LENS ACH 40 x 80 MgF2 TS RoHS	40.00	80.00	70.75	BaFN10-SF10	MTF Curve	NT45-105	$89.50
▪ LENS ACH 40 x 60 MgF2 TS RoHS	40.00	60.00	50.29	SK11-SF5	MTF Curve	NT45-218	$91.50

Edmund optics negative achromats: F2 = -1.25cm D2 = 0.625cm

Description	Dia. (mm)	E.F.L. (mm)	Back F.L. (mm)	Glass Type	Stock Number	Price *
▪ LENS ACH 6.25 x -12.5 MgF2 TS RoHS	6.25	-12.5	-12.89	BaF10-FD10	NT45-420	$60.40

With this, we complete the paraxial design. As advertised, in this part we analyzed the chosen design both analytically and quantitatively, came up with design analysis plots that helped us in choosing the lenses. We also made sure that we have satisfied the initially proposed specifications.

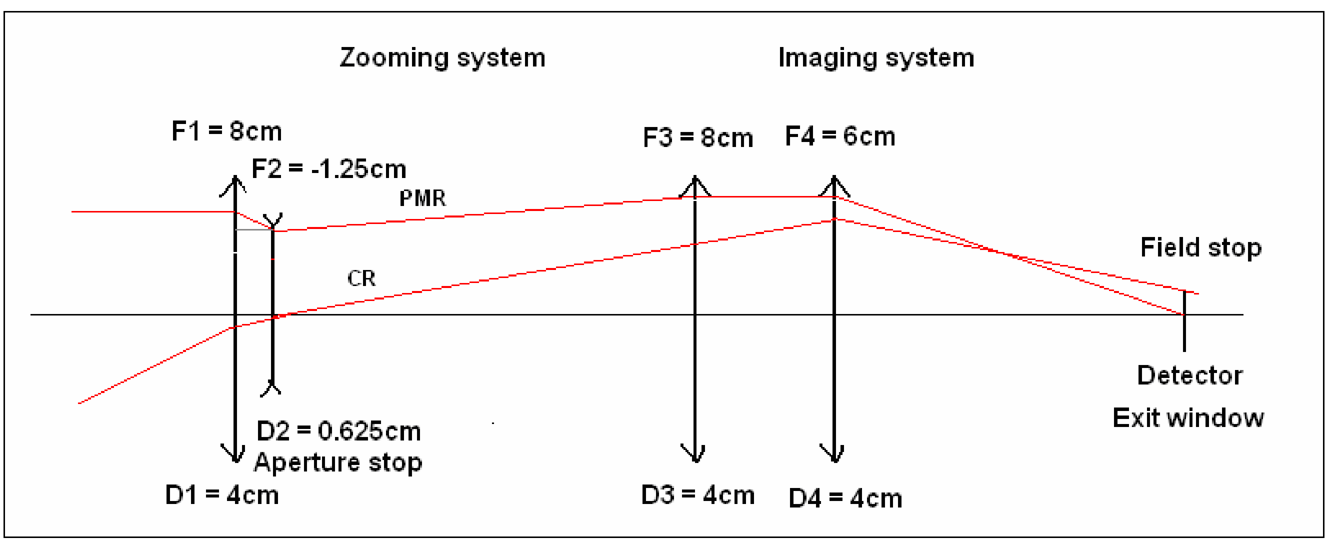
2.3 Thicken/Stops

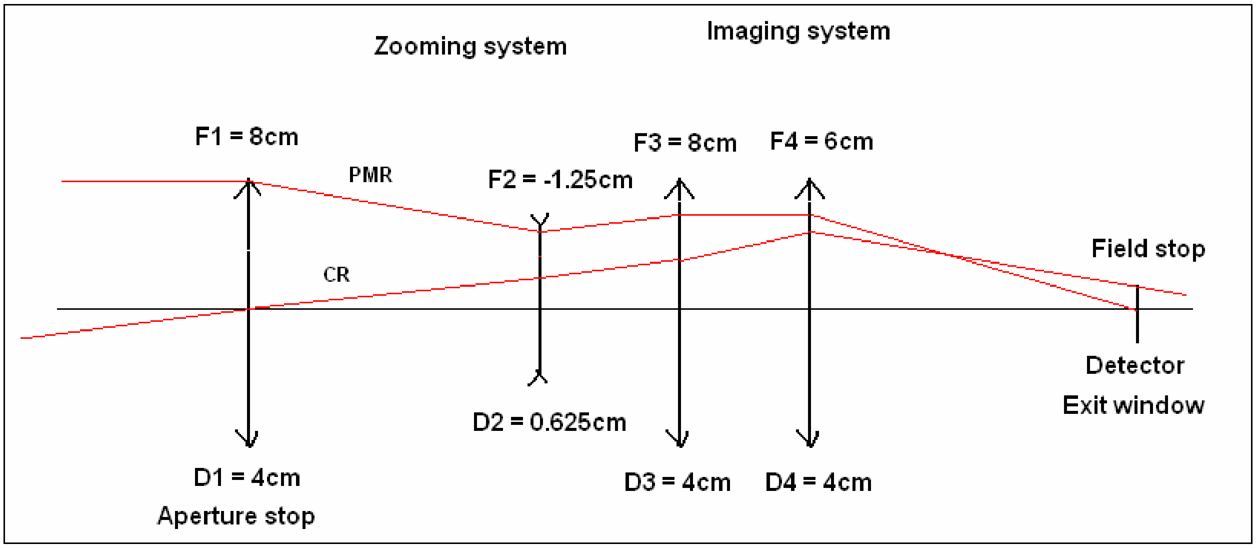
The goal of this section is to first introduce stops into the paraxial design, and then to calculate pertinent quantities like resolution, NA, etc. Once that's done, the paraxial lenses will be replaced by their thick versions. In essence, the idea here is to make our imaging system more realistic.

The detector should necessarily be the **field stop**, as we don't want to leave any area of the detector unused. Consequently, the **exit window** is also the CCD detector. The **entrance window** can now be found by determining the image of the field stop in the object space.

Since we have a dynamic lens arrangement that changes during operation, the **Aperture Stop** is not always the same. It depends on the location and size of the negative lens. Further, note that we don't have the freedom of placing a physical stop (iris) in between the two convex lenses as that would obstruct the motion of the negative lens.

Consider the following two ray diagrams. The concave lens acts as the aperture stop when it is close to the front lens. As the concave lens is moved away from the front lens, we see that rays are being cut off not by the concave lens, but by the first convex lens. Implies, the **paraxial marginal ray** and the **chief ray** are heavily dependent on the zoom position. But, note that the chief ray, regardless of the zoom position, must pass through the edge of the CCD detector, as the detector *must* be the field stop (we want to use the entire CCD array at all zoom positions!)





When the imaging system is used without the zoom lens, clearly, F4 acts as the aperture stop. In such a system, the resolution would decrease for off axis points, as the image plane cone angle (and hence, NAi) decreases. This can be tackled by using a telecentric design where the single imaging lens is replaced by two lenses separated by the sum of their focal lengths. An iris is placed exactly in the back/front focal plane of the first/second lens.

When the imaging system is used with the zoom lens, with the current design, achieving telecentric condition is tricky. First, because the zoom lens is not static. Depending on the position of the middle negative lens, the throw of the system varies, and if we were to insist on making the zoom lens telecentric, we'll have to design a yet another mechanical compensation system, that would literally displace the aperture stop based on the location of the negative lens. Besides, accomplishing telecentricity with an afocal system designed with a negative and a positive lens is different from that of two positive lenses. Note that in the two positive lens case, the aperture stop can be placed in back/front focal plane of first/second lens. This is not true in our design.

Since this camera is designed to see objects at infinity, all incoming wavefronts are ~plane. They (obviously) could have different **k** vector directions, though. So, the input cone angle is ~0. Implies, input NA is 0, and has no big importance. What is important is actually the image space NA. Since the zoom system is always afocal, as noted before, the imaging lens always has its image at its back focal plane.

Image space:

Image space NA = nsin(theta) = 1 * sin((D4/2)/F4) = sin(2/6) = 0.3272

Resolution = 1.22 * lambda / 2 * NA

= 1.22 * .5 x 10^-6 / (2 x 0.3272)

= ~0.93 microns.

F# in image space (infinite conjugate condition) = 1/(2*NA) = f/D = 6/4 = 1.5

Depth of focus in image space:

DOF = 1.2 * lambda / (NA^2) = 1.2 * 0.5 * 10^-6 / (0.3272)^2 = 5.6um (image space)

The CCD parameters should be chosen carefully so as not to introduce aliasing. The pixels of the CCD are essentially sampling the spatial field incident on it. In order to avoid aliasing, this sampling should be done atleast at nyquist. In other words, the spatial frequency of the CCD pixels should be atleast twice the spatial (not temporal!) frequency of the field. Fourier optics gives us a yet another way of looking at this. An undersampled system (aliasing! – bad!) is one in which the width of a single CCD pixel is wider than the psf of the imaging system. In the frequency domain, the successive spectral orders over lap, and higher frequencies get wrongly represented as lower frequencies. In a critically sampled system (OK!), the pixel width and the psf width are just about equal. The successive spectral orders are very close (their tails almost touch), but they don't overlap. On the other hand, in an oversampled system (Good!), the pixel width is much smaller than the psf width, and the frequency orders are widely separated in the spectral domain. In reality, most carefully designed systems are over sampled, and so will be ours.

Consider a 3 cm x 2 cm CCD detector with pixel width 10um (including pixel spacing).

Aspect ratio = 3:2

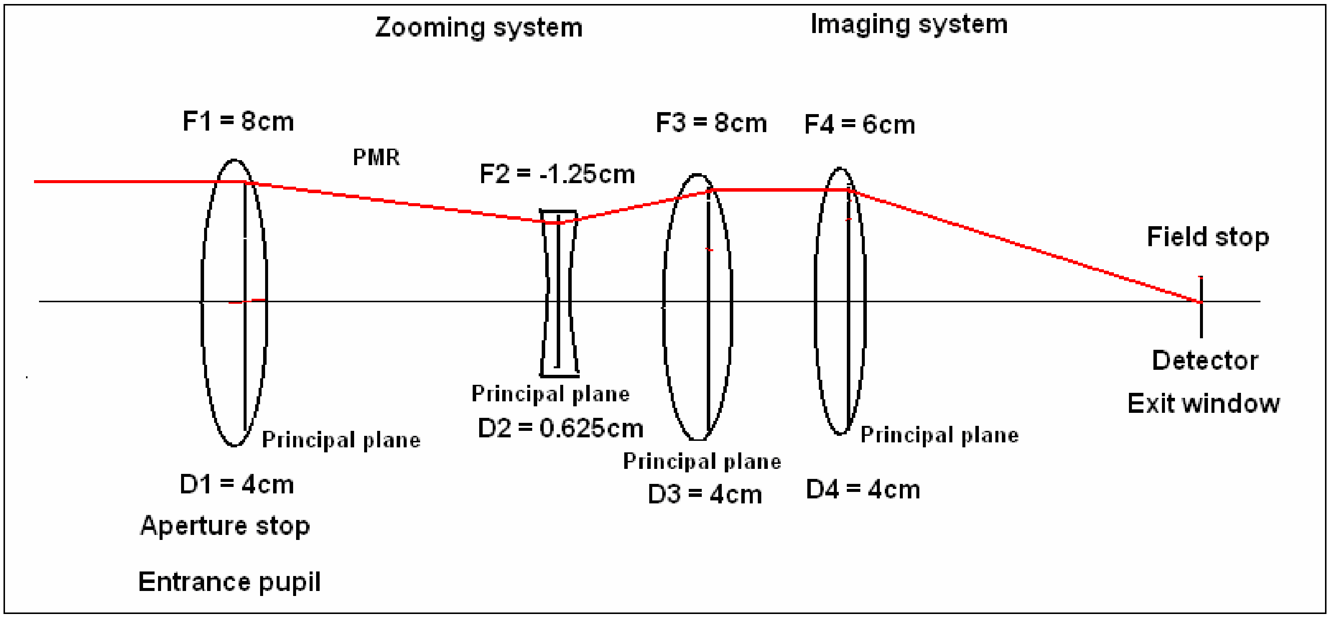
Implies, number of columns = 3 * number of rows = 3 x 10^-2/10^-5 = 3000

3000 x 2000 pixels = 6 Megapixel camera!

Now, a 10um CCD pixel will continue to be in the over sampled regime until the psf gets smaller that 10um. From nyquist, this means that all spatial frequencies lesser than 1 / (2 * 10u) can be accurately represented. In order to prove that this spatial pixel resolution is sufficient, we recall that the smallest possible width of psf bears an inverse fourier transform relation with the pupil width. Strictly speaking, this is true only for coherent systems. In an incoherent system, the psf width approximately goes as the inverse of the optical transfer function, which is the autocorrelation of the pupil function. Nevertheless, they are close.

Hence, for the system to be critically sampled, the pupil function diameter should go as the inverse of the pixel size, which is a very huge number when compared to our designed pupil. As our pupil is small, the psf is large – much larger than the pixel width. Therefore, we conclude that the system is over sampled relative to the resolution of the optics.

We now move away from the thin lens approximation and start using thick lenses. One key point to consider is that, the moment thin lens approximation is violated, the principal planes of a lens are not necessarily in the physical edges of the lens. [Implies, the front and back focal lengths are not necessarily equal to the effective focal length] So, we have to make sure that the distances calculated before are applied from the principal planes, instead of the physical location of lenses.



To start with, we use symmetric achromatic biconvex and biconcave lenses. Because of the symmetry, the principal planes are always located inside the lens. (Slightly away from the center). The distances can be calculated accurately from the thickness, curvatures and refractive index of the lenses.

Specifically,

$$h_1 = -\frac{f(n-1)d}{R_2 n} \qquad h_2 = -\frac{f(n-1)d}{R_1 n}$$

h1 and h2 are the distances of the principal planes from the physical edges of lens. f,n,d and R represent the focal length, refractive index, thickness, and radius of curvature respectively. In general, if we were to design a lens, we would first decide on the glass (hence n), calculate the curvatures, and decide on the thickness. Once that's done, we can either look around if we can find that particular lens in the market; or, we'll have to make a special order to design the lens we want (very expensive option)

By making sure that the lenses we want are readily available from Edmund optics, we have made sure that we don't run in to such problems.

Edmund optics positive achromats: F1 = F3 = 8cm and F4 = 6cm D1 = D3 = 4cm D4 = 4cm

Description	Dia. (mm)	E.F.L. (mm)	Back F.L. (mm)	Glass Type	MTF Curve	Stock Number	Price *
▪ LENS ACH 40 x 80 MgF2 TS RoHS	40.00	80.00	70.75	BaFN10-SF10	MTF Curve	NT45-105	$89.50
▪ LENS ACH 40 x 60 MgF2 TS RoHS	40.00	60.00	50.29	SK11-SF5	MTF Curve	NT45-218	$91.50

Edmund optics negative achromats: F2 = -1.25cm D2 = 0.625cm

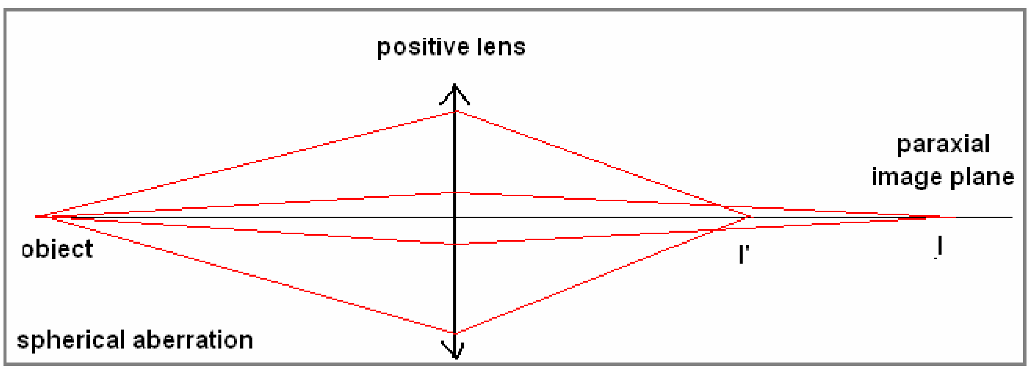
Description	Dia. (mm)	E.F.L. (mm)	Back F.L. (mm)	Glass Type	Stock Number	Price *
▪ LENS ACH 6.25 x -12.5 MgF2 TS RoHS	6.25	-12.5	-12.89	BaF10-FD10	NT45-420	$60.40

We are now done with the thicklens design – We know exactly what lenses to use and where to place them. We also numerically characterized a few important metrics like resolution, depth of field, NA, and F/#, which inturn helped us in determining the configuration of the CCD detector. But, we did not do much for correcting aberrations, other than using achromatic lenses. We expect to see many more aberrations in reality. We'll deal with aberrations once we get into the next section, where we'll be plugging our above design into ZEMAX.

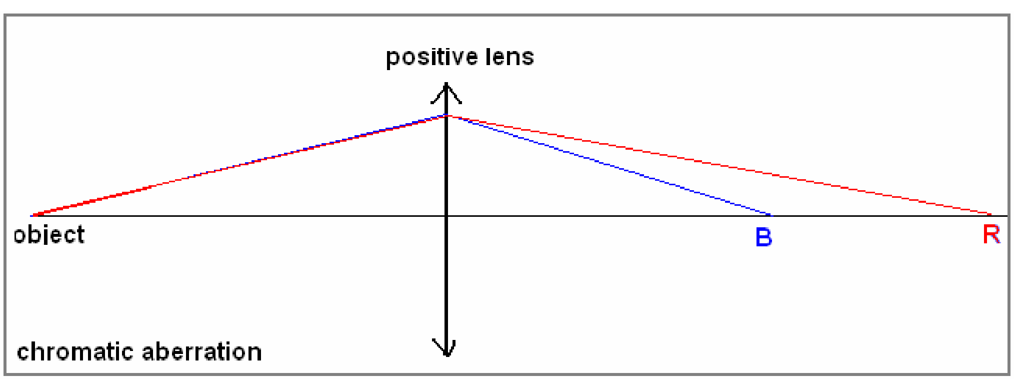
Before jumping on to the ZEMAX design, we'll now have a quick look into a few important aberrations that could potentially plague our system. A clear understanding of what aberrations a system has is imperative to come up with optimum solutions to minimize (if not eliminate) them.

Aberrations

- One of the main goals of this project is to come up with an "aberration corrected" camera lens design



- Rays (from a same point) hitting different regions of the lens get focused at different points! Implies, there is no single image plane in the non-paraxial limit.
- Spherical aberration can be minimized by stopping down the aperture. But, only at the cost of minimizing the NA, thereby degrading the resolution of the imaging system.

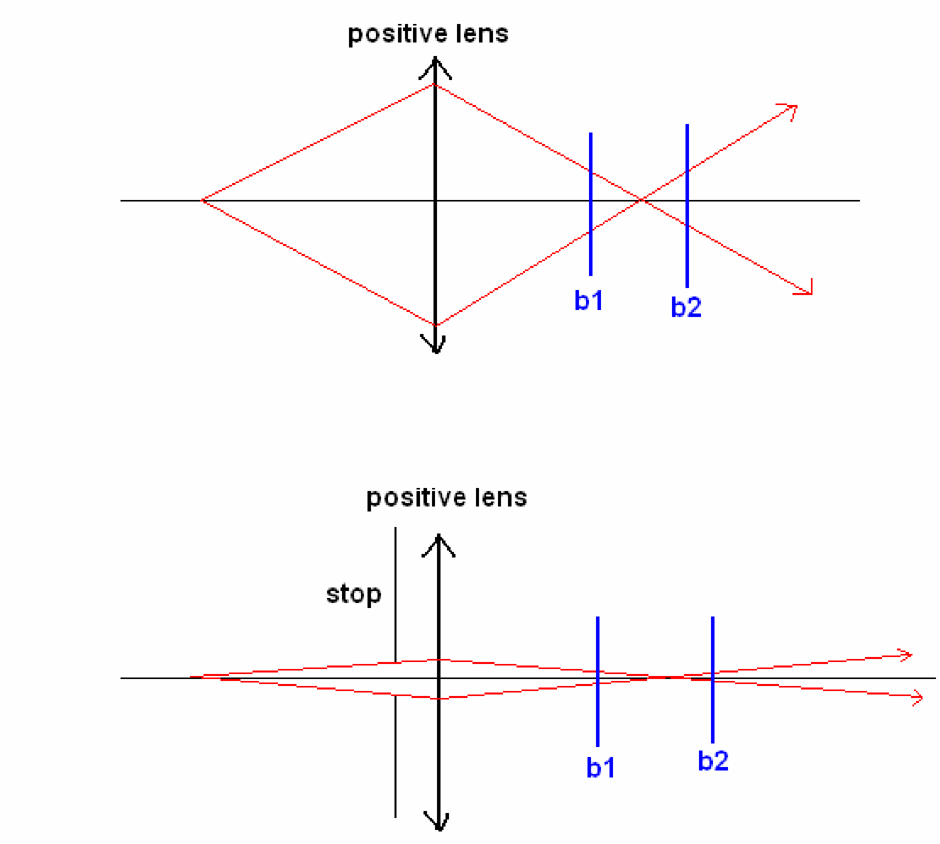


- Refractive index of most materials increases with frequency, which means that a same lens might have more power for a blue ray than for a red ray. Implies, colored objects will not be imaged properly, unless “some special” techniques (like achromatization) are used.
- Off axis aberrations like coma and astigmatism also plague an imaging system.

Resolution - Depth of field trade off

- Resolution is proportional to NA (n*sin(half cone angle)), while the depth of field is inversely proportional to NA^2. Implies, higher the resolution, lower the depth of field.

- Examples: Microscopes have great resolution but poor depth of field.
  Pinhole cameras have great depth of field but poor resolution



Resolution - Depth of field trade off

- All this can be visualized by just comparing the diameter of the blurs (b1 and b2) in the following two diagrams. When the aperture is stopped down (NA, resolution decreases), but the diameter of the blur also decreases. Implies, depth of field increases.
- For obtaining infinite resolution (resolve all frequencies!), the diameter of the exit pupil should be infinite (cone angle literally tends to 90 degree!)

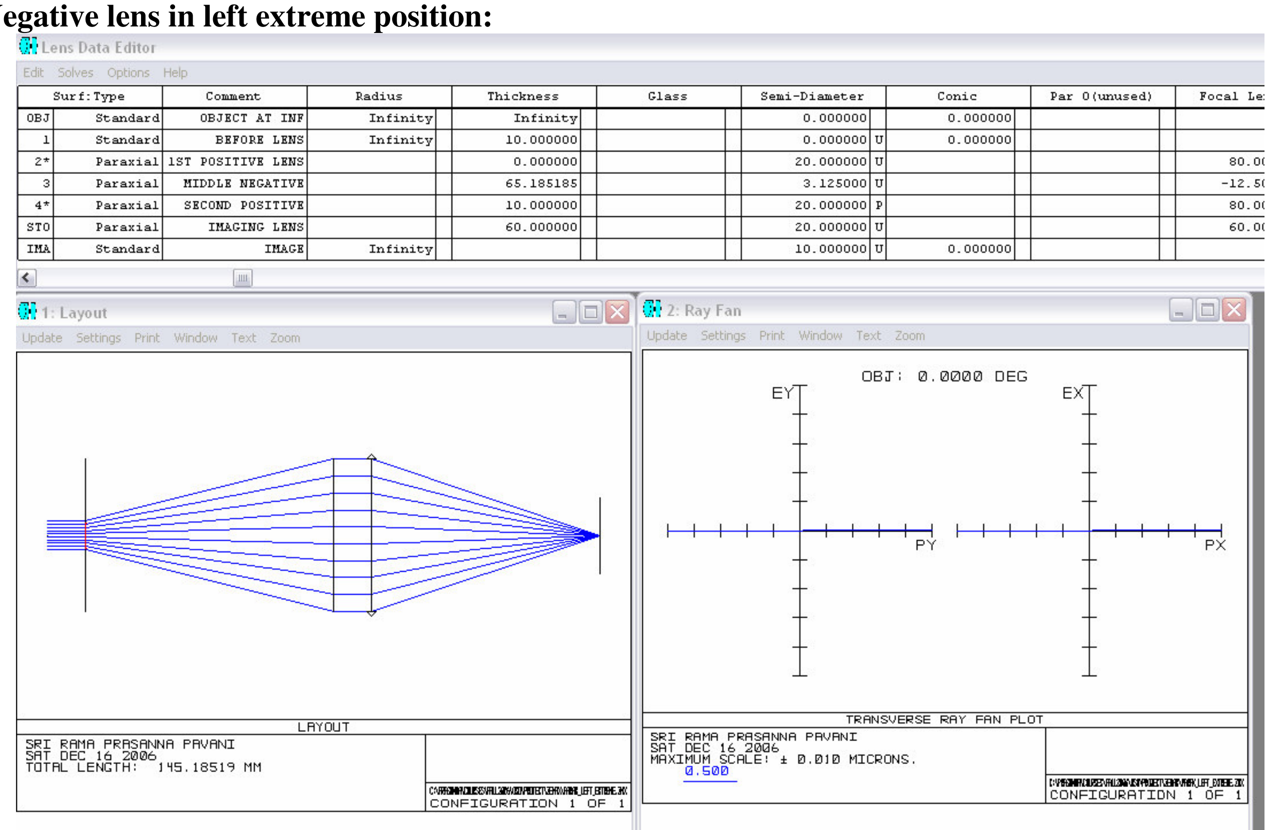
2.4 ZEMAX design

We pretty much have the complete design with us now. But, as the design was done in the paraxial world, we completely ignored aberrations. Building an aberration corrected design is many times an optimization (number crunching!) problem, and so beyond the scope of paraxial design tools. The idea here is to do our best on the paraxial design (hopefully, we already did that), and to ask ZEMAX to optimize for best results (Diffraction limit!). Assume wavelength = 0.5um.

The goal of this section, therefore, is to analyze the ray/wavefront abberations quantitatively and to comeup with the best possible aberration corrected design that satisfies our specifications. To get started, we'll model our paraxial system in ZEMAX and see if our paraxial system works or not. Then, we'll replace the paraxial lenses with thick achromatic lenses that we chose in the previous section, and analyze the aberration characteristics. Finally, we'll optimize our design to reach diffraction limited performance. (While doing so, we might have to compromise on some specifications)

We now recall that the system is perfectly afocal (without mechanical compensation) when the negative lens is in either of its extreme positions.

Negative lens in left extreme position:


Lens Data Editor

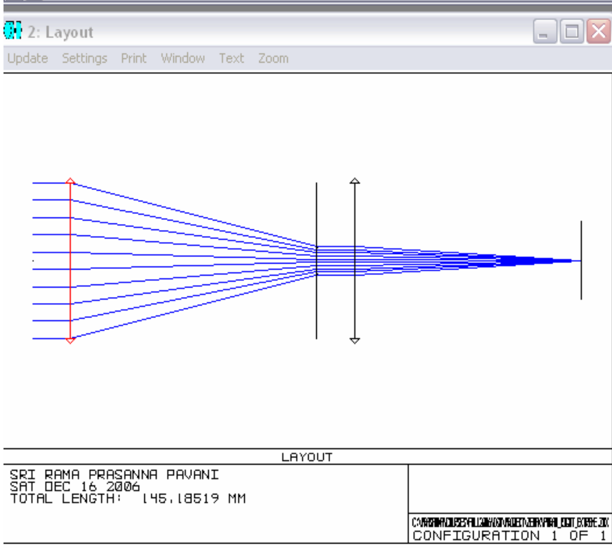
Edit Solves Options Help

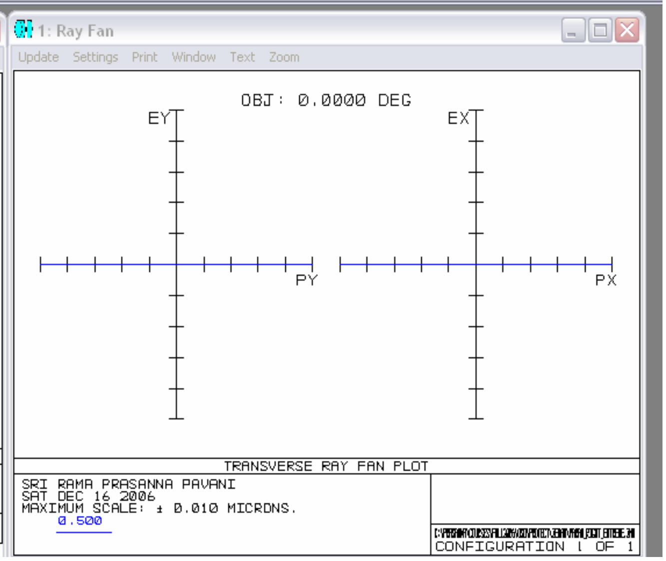
	Surf:Type	Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 0(unused)	Focal Le
OBJ	Standard	OBJECT AT INF	Infinity	Infinity		0.000000	0.000000		
1	Standard	BEFORE LENS	Infinity	10.000000		0.000000 U	0.000000		
2*	Paraxial	1ST POSITIVE LENS		0.000000		20.000000 U			80.0
3	Paraxial	MIDDLE NEGATIVE		65.185185		3.125000 U			-12.5
4*	Paraxial	SECOND POSITIVE		10.000000		20.000000 P			80.0
STO	Paraxial	IMAGING LENS		60.000000		20.000000 U			60.0
IMA	Standard	IMAGE	Infinity			10.000000 U	0.000000		

Negative lens in right extreme position:

Lens Data Editor

Surf	Type	Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 0(unused)	Focal Len
OBJ	Standard	OBJECT AT INF	Infinity	Infinity		0.000000	0.000000		
1	Standard	BEFORE LENS	Infinity	10.000000		0.000000 U	0.000000		
STO	Paraxial	1ST POSITIVE		65.185185		20.000000 U			80.00
3	Paraxial	MIDDLE NEGATIVE		0.000000		3.125000 U			-12.50
4*	Paraxial	2ND POSITIE LENS		10.000000		20.000000 U			80.00
5	Paraxial	IMAGING LENS		60.000000		20.000000 U			60.00
IMA	Standard	IMAGE	Infinity			10.000000 U	0.000000		



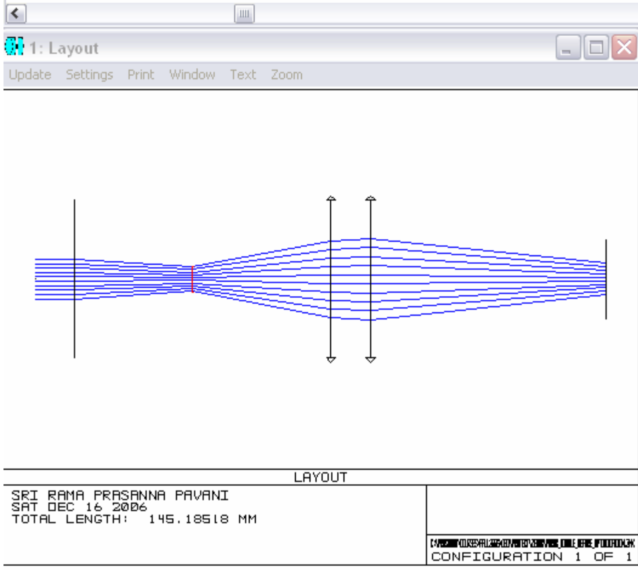


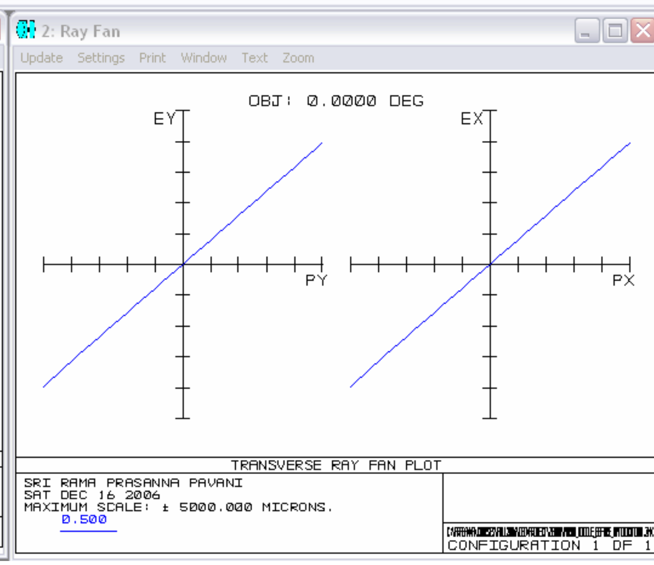
When the negative lens is moved somewhere to the middle, the zoom lens system is not afocal anymore, and so, we expect a misfocus in the image plane.

Negative lens somewhere in between the two positive lenses (before mechanical compensation)

Lens Data Editor

Surf	Type	Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 0(unused)	Focal Le
OBJ	Standard	OBJECT AT INF	Infinity	Infinity		0.000000	0.000000		
1	Standard	BEFORE LENS	Infinity	10.000000		0.001000 U	0.000000		
2*	Paraxial	1ST POSITIVE LENS		30.000000		20.000000 U			80.0
STO	Paraxial	MIDDLE NEGATIVE		35.185185		3.125000 U			-12.5
4	Paraxial	SECOND POSITIVE		10.000000		20.000000 U			80.0
5	Paraxial	IMAGING LENS		60.000000		20.000000 U			60.0
IMA	Standard	IMAGE	Infinity			10.000000 U	0.000000		



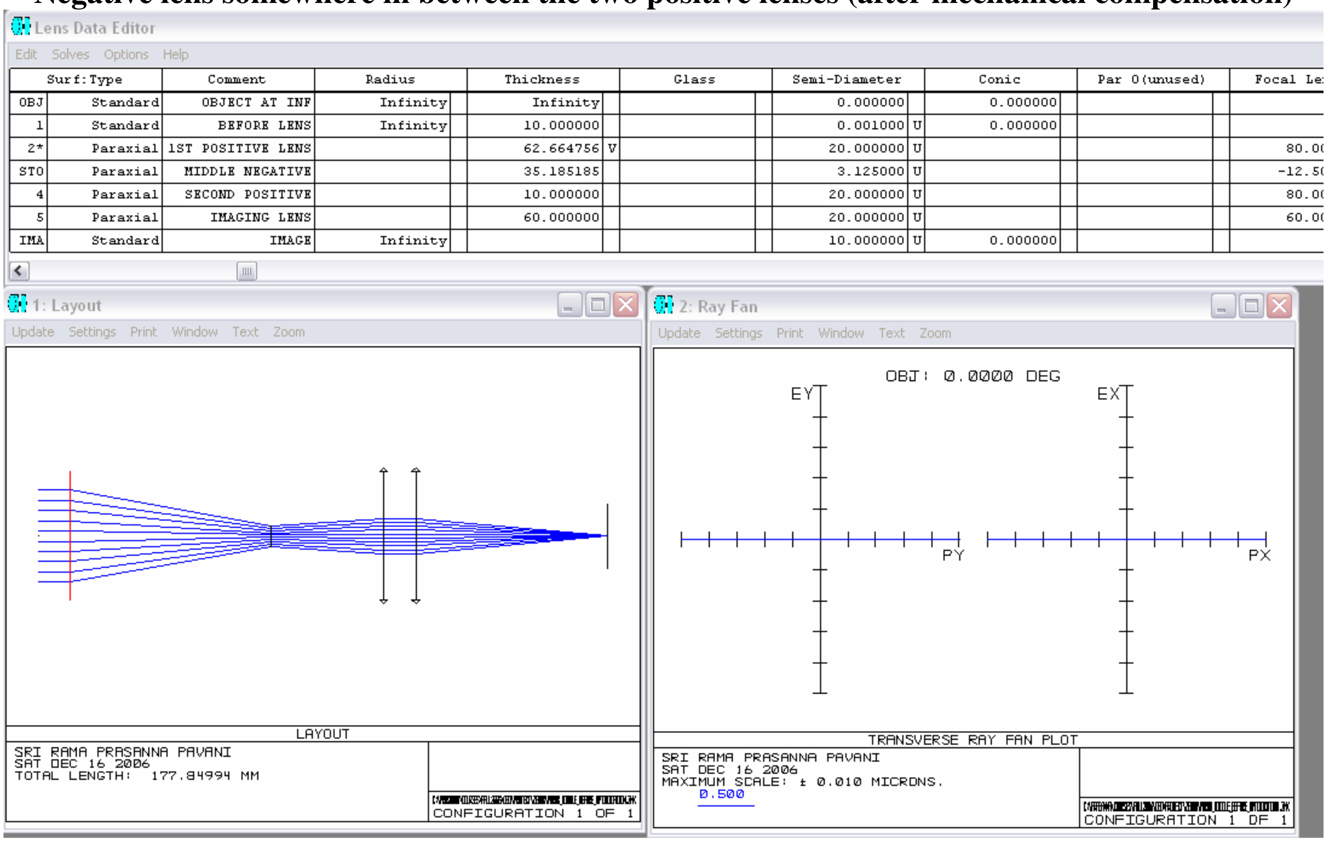


In order to get rid of this misfocus, the zoom lens has to be made afocal again by using mechanical compensation. One might wonder why the image plane should not be moved back to get rid of this misfocus. Doing so would mean that the detector is not necessarily at the back focal plane of the imaging lens (for all zoom values), which would require a mechanical compensation system in the imaging system part. Since this "detachable zoom" camera has been designed such that the cost of the camera part is very less, we do not want to introduce a mechanical compensation system in the camera part. Instead, we'd like to have it in the zoom lens part such that the zoom lens is always afocal regardless of the position of the negative lens.

We now introduce a mechanical compensation system to move the front positive lens forward in order to make the system afocal again. ZEMAX optimizer is used optimize the distance between the first positive lens and the middle negative lens (first lens thickness, in ZEMAX lingo) in order to accomplish mechanical compensation.

The result is shown below. There's no misfocus anymore. Note that this has been accomplished by changing the first lens thickness from ~3cm to ~6cm

Negative lens somewhere in between the two positive lenses (after mechanical compensation)



Surf:Type		Comment	Radius	Thickness		Glass	Semi-Diameter		Conic	Par 0(unused)	Focal Le
OBJ	Standard	OBJECT AT INF	Infinity	Infinity			0.000000		0.000000		
1	Standard	BEFORE LENS	Infinity	10.000000			0.001000	U	0.000000		
2*	Paraxial	1ST POSITIVE LENS		62.664756	V		20.000000	U			80.00
STO	Paraxial	MIDDLE NEGATIVE		35.185185			3.125000	U			-12.50
4	Paraxial	SECOND POSITIVE		10.000000			20.000000	U			80.00
5	Paraxial	IMAGING LENS		60.000000			20.000000	U			60.00
IMA	Standard	IMAGE	Infinity				10.000000	U	0.000000		

With the above analysis, we have (hopefully) convinced ourselves that ZEMAX agrees with the manual paraxial design we did earlier. It's time to stick in thick lenses. As noted earlier, we make sure that the distances of separation of lenses are based on the front and back focal lengths (not the effective focal lengths!)

Edmund optics positive achromats: F1 = F3 = 8cm and F4 = 6cm D1 = D3 = 4cm D4 = 4cm

Description	Dia. (mm)	E.F.L. (mm)	Back F.L. (mm)	Glass Type	MTF Curve	Stock Number	Price *
▪ LENS ACH 40 x 80 MgF2 TS RoHS	40.00	80.00	70.75	BaFN10-SF10	MTF Curve	NT45-105	$89.50
▪ LENS ACH 40 x 60 MgF2 TS RoHS	40.00	60.00	50.29	SK11-SF5	MTF Curve	NT45-218	$91.50

Edmund optics negative achromats: F2 = -1.25cm D2 = 0.625cm

Description	Dia. (mm)	E.F.L. (mm)	Back F.L. (mm)	Glass Type	Stock Number	Price *
▪ LENS ACH 6.25 x -12.5 MgF2 TS RoHS	6.25	-12.5	-12.89	BaF10-FD10	NT45-420	$60.40

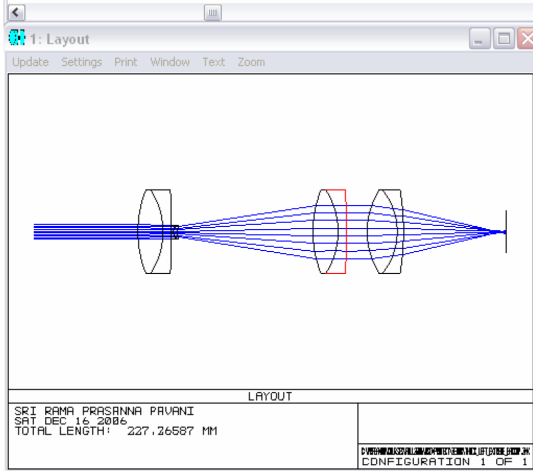
The above achromatic lenses are picked from ZEMAX lens catalog. The orientation of the lenses is important to minimize spherical aberration. The more curved surface should always point towards the plane wave. A quick look at the ray diagrams (drawn in earlier sections) would reveal that lenses F1, F2, and F4 can be plugged in as such, while the lens F3 has to be flipped.

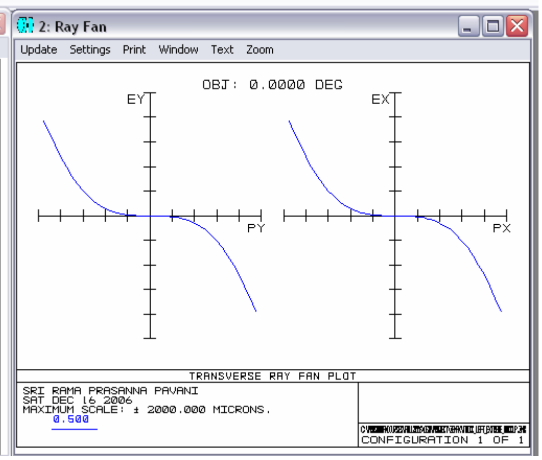
Negative lens in left extreme position (Before flipping F3)

Lens Data Editor

Edit Solves Options Help

Surf	Type	Comment	Radius	Thickness		Glass	Semi-Diameter		Conic	Par 0(unused)
OBJ	Standard	OBJECT AT INF	Infinity	Infinity			0.000000		0.000000	
1	Standard	BEFORE LENS	Infinity	50.000000			0.001000	U	0.000000	
2*	Standard	45105	53.760000	12.070000		BAFN10	20.000000	U	0.000000	
3*	Standard		-36.730000	4.000000		SF10	20.000000	U	0.000000	
4*	Standard		-435.850000	0.000000			20.000000	U	0.000000	
STO*	Standard	45420	-24.660000	1.000000		BAFN10	3.125000	U	0.000000	
6*	Standard		4.240000	2.000000		SF10	3.125000	U	0.000000	
7*	Standard		11.250000	65.125000			3.125000	U	0.000000	
8*	Standard	45105	53.760000	12.070000		BAFN10	20.000000	U	0.000000	
9*	Standard		-36.730000	4.000000		SF10	20.000000	U	0.000000	
10*	Standard		-435.850000	10.000000			20.000000	U	0.000000	
11*	Standard	45218	37.330000	14.460000		SK11	20.000000	U	0.000000	
12*	Standard		-31.540000	3.000000		SF5	20.000000	U	0.000000	
13*	Standard		-124.510000	49.540873	M		20.000000	U	0.000000	
IMA	Standard	IMAGE	Infinity				10.000000	U	0.000000	





Negative lens in left extreme position (after flipping F3)

Lens Data Editor

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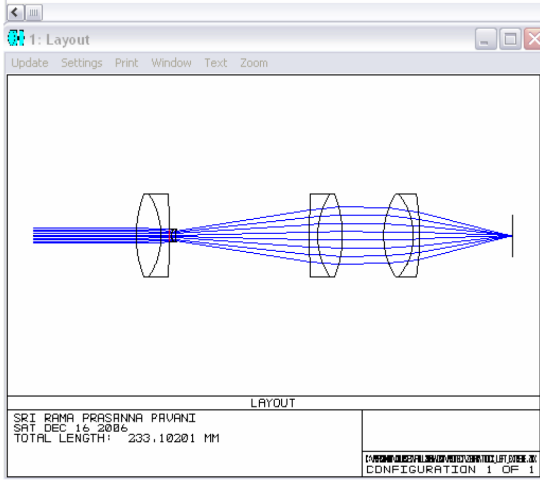
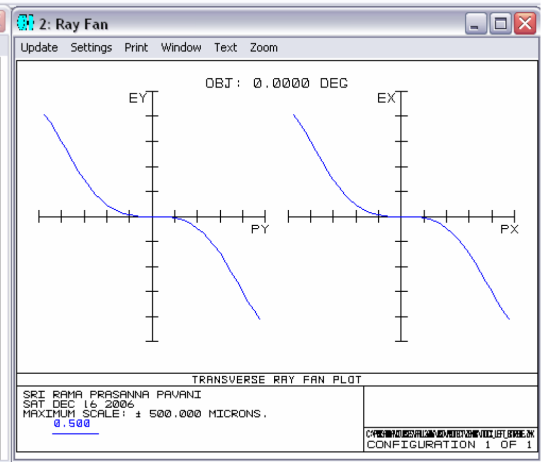
Surf	Type	Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 0(unused)
OBJ	Standard	OBJECT AT INF	Infinity	Infinity		0.000000	0.000000	
1	Standard	BEFORE LENS	Infinity	50.000000		0.001000 U	0.000000	
2*	Standard	45105	53.760000	12.070000	BAFN10	20.000000 U	0.000000	
3*	Standard		-36.730000	4.000000	SF10	20.000000 U	0.000000	
4*	Standard		-435.850000	0.000000		20.000000 U	0.000000	
STO*	Standard	45420	-24.660000	1.000000	BAFN10	3.125000 U	0.000000	
6*	Standard		4.240000	2.000000	SF10	3.125000 U	0.000000	
7*	Standard		11.250000	65.125000		3.125000 U	0.000000	
8*	Standard	45105	435.850000	4.000000	SF10	20.000000 U	0.000000	
9*	Standard		36.730000	12.070000	BAFN10	20.000000 U	0.000000	
10*	Standard		-53.760000	20.000000		20.000000 U	0.000000	
11*	Standard	45218	37.330000	14.460000	SK11	20.000000 U	0.000000	
12*	Standard		-31.540000	3.000000	SF5	20.000000 U	0.000000	
13*	Standard		-124.510000	45.377009 M		20.000000 U	0.000000	
IMA	Standard	IMAGE	Infinity			10.000000 U	0.000000	





After adding misfocus to correct spherical aberration

Lens Data Editor

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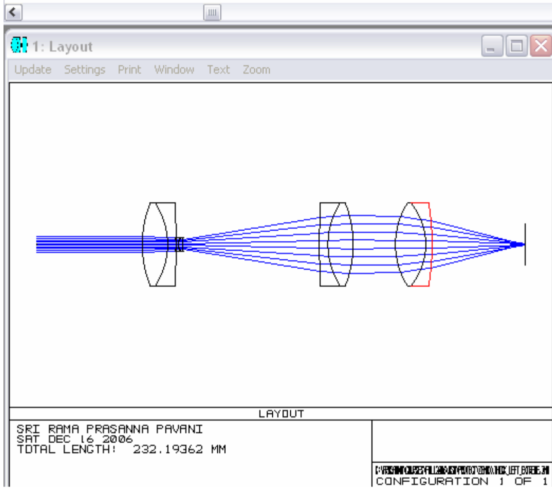
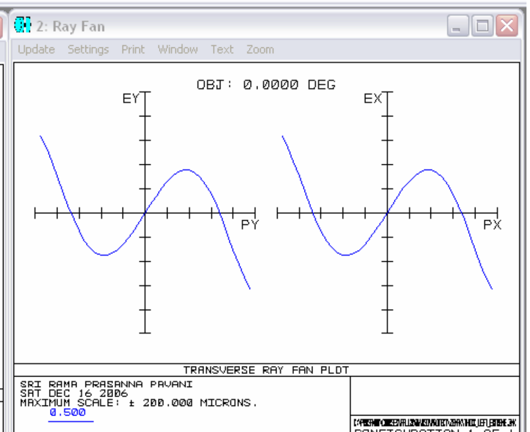
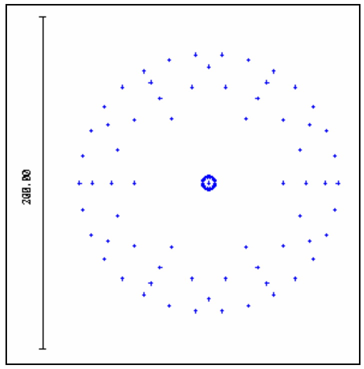
Surf	Type	Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 0(unused)
OBJ	Standard	OBJECT AT INF	Infinity	Infinity		0.000000	0.000000	
1	Standard	BEFORE LENS	Infinity	50.000000		0.001000 U	0.000000	
2*	Standard	45105	53.760000	12.070000	BAFN10	20.000000 U	0.000000	
3*	Standard		-36.730000	4.000000	SF10	20.000000 U	0.000000	
4*	Standard		-435.850000	0.000000		20.000000 U	0.000000	
STO*	Standard	45420	-24.660000	1.000000	BAFN10	3.125000 U	0.000000	
6*	Standard		4.240000	2.000000	SF10	3.125000 U	0.000000	
7*	Standard		11.250000	65.125000		3.125000 U	0.000000	
8*	Standard	45105	435.850000	4.000000	SF10	20.000000 U	0.000000	
9*	Standard		36.730000	12.070000	BAFN10	20.000000 U	0.000000	
10*	Standard		-53.760000	20.000000		20.000000 U	0.000000	
11*	Standard	45218	37.330000	14.460000	SK11	20.000000 U	0.000000	
12*	Standard		-31.540000	3.000000	SF5	20.000000 U	0.000000	
13*	Standard		-124.510000	44.468618 V		20.000000 U	0.000000	
IMA	Standard	IMAGE	Infinity			10.000000 U	0.000000	





The aberration is largely spherical. Note that the maximum spherical aberration is ~1546um when F3 is not flipped! After flipping F3, just as expected, the spherical has reduced to ~408um! The spherical aberration can be reduced further by adding intentional misfocus. We use optimizer to optimize the image plane distance to minimize SA. After optimization, the maximum spherical aberration is ~126.42um. (Much better than before)



Though we have done a reasonable good job in reducing the spherical aberration from ~1546um to ~126.42um, we are no where near the diffraction limit yet. In order to minimize the aberration further, we start stopping down the system. Note that SA is proportional to the cone angle, but we should realize that by stopping down, we are compromising the system NA (and hence the resolution). As the system is too far from the diffraction limit now, ZEMAX refuses to show the "diffraction encircled energy", complaining that the data is too inaccurate.

When we stop down the imaging lens to 20mm diameter, max SA reduces to ~60.44um, and we can see how well the system performs relative to the diffraction limit.

Stop diameter: 20mm

Lens Data Editor

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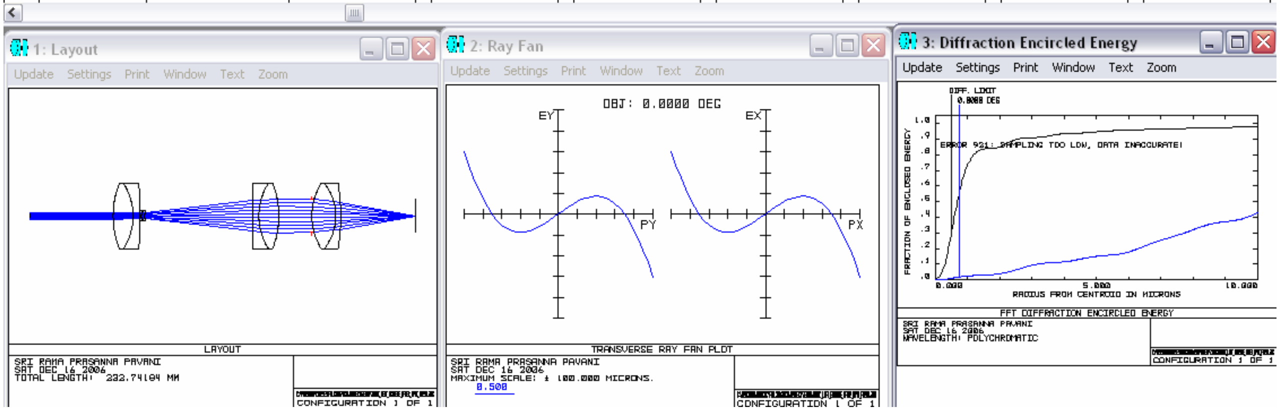
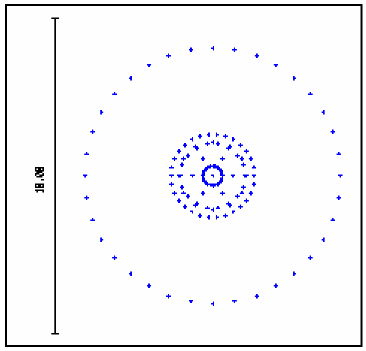
Surf:Type		Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 0(unused)	Par 1(unused)
OBJ	Standard	OBJECT AT INF	Infinity	Infinity		0.000000	0.000000		
1	Standard	BEFORE LENS	Infinity	50.000000		1.000000 U	0.000000		
2*	Standard	45105	53.760000	12.070000	BAFN10	20.000000 U	0.000000		
3*	Standard		-36.730000	4.000000	SF10	20.000000 U	0.000000		
4*	Standard		-435.850000	0.000000		20.000000 U	0.000000		
5*	Standard	45420	-24.660000	1.000000	BAFN10	3.125000 U	0.000000		
6*	Standard		4.240000	2.000000	SF10	3.125000 U	0.000000		
7*	Standard		11.250000	65.125000		3.125000 U	0.000000		
8*	Standard	45105	435.850000	4.000000	SF10	20.000000 U	0.000000		
9*	Standard		36.730000	12.070000	BAFN10	20.000000 U	0.000000		
10*	Standard		-53.760000	20.000000		20.000000 U	0.000000		
STO	Standard		Infinity	0.000000		10.000000 U	0.000000		
12*	Standard	45218	37.330000	14.460000	SK11	20.000000 U	0.000000		
13*	Standard		-31.540000	3.000000	SF5	20.000000 U	0.000000		
14*	Standard		-124.510000	45.016839 V		20.000000 U	0.000000		

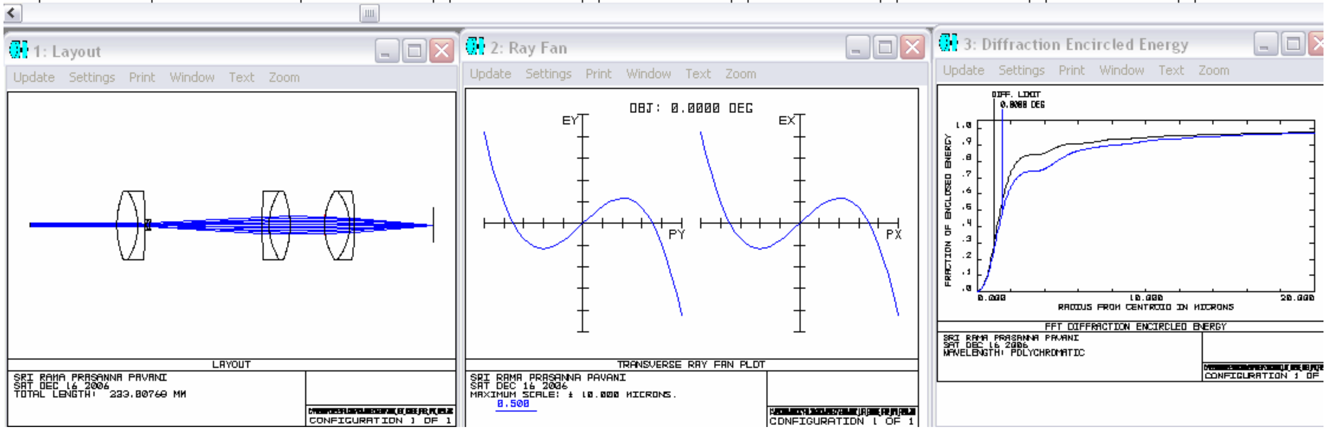


Upon stopping the system down more and more, the system tends to approach the diffraction limit (only at the cost of resolution!). For instance, stopping down to 10mm reduces the spherical aberration to ~8.4um. **We reach diffraction limit when the stop diameter is less than ~7.8mm**



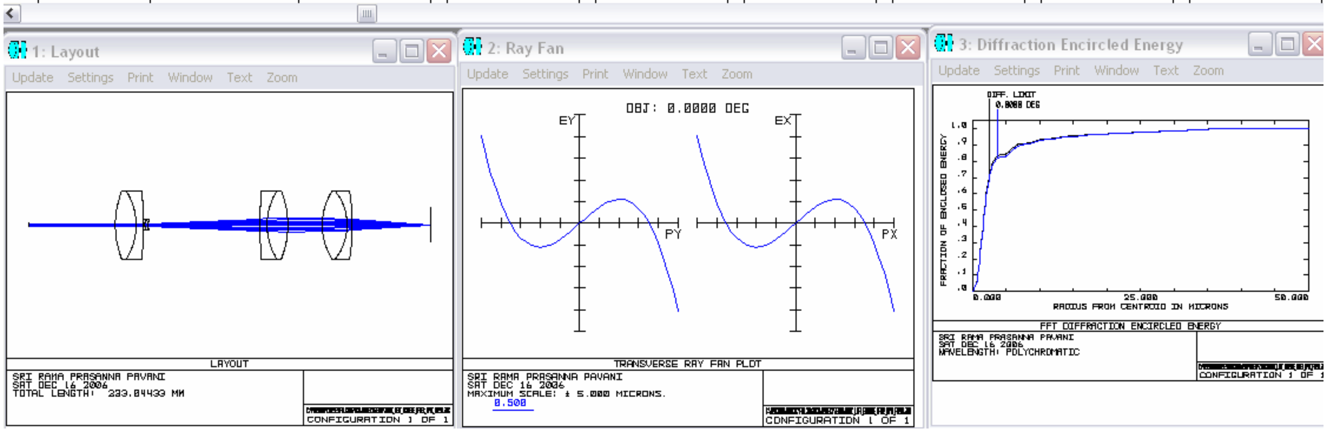
Stop diameter: 10mm

Surf	Surf:Type	Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 0(unused)	Par 1(unused)
OBJ	Standard	OBJECT AT INF	Infinity	Infinity		0.000000	0.000000		
1	Standard	BEFORE LENS	Infinity	50.000000		1.000000 U	0.000000		
2*	Standard	45105	53.760000	12.070000	BAFN10	20.000000 U	0.000000		
3*	Standard		-36.730000	4.000000	SF10	20.000000 U	0.000000		
4*	Standard		-435.850000	0.000000		20.000000 U	0.000000		
5*	Standard	45420	-24.660000	1.000000	BAFN10	3.125000 U	0.000000		
6*	Standard		4.240000	2.000000	SF10	3.125000 U	0.000000		
7*	Standard		11.250000	65.125000		3.125000 U	0.000000		
8*	Standard	45105	435.850000	4.000000	SF10	20.000000 U	0.000000		
9*	Standard		36.730000	12.070000	BAFN10	20.000000 U	0.000000		
10*	Standard		-53.760000	20.000000		20.000000 U	0.000000		
STO	Standard		Infinity	0.000000		5.000000 U	0.000000		
12*	Standard	45218	37.330000	14.460000	SK11	20.000000 U	0.000000		
13*	Standard		-31.540000	3.000000	SF5	20.000000 U	0.000000		
14*	Standard		-124.510000	45.282678 V		20.000000 U	0.000000		



Stop diameter: 7.8mm

	Surf:Type	Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 0(unused)	Par 1(unused)
OBJ	Standard	OBJECT AT INF	Infinity	Infinity		0.000000	0.000000		
1	Standard	BEFORE LENS	Infinity	50.000000		1.000000 U	0.000000		
2*	Standard	45105	53.760000	12.070000	BAFN10	20.000000 U	0.000000		
3*	Standard		-36.730000	4.000000	SF10	20.000000 U	0.000000		
4*	Standard		-435.850000	0.000000		20.000000 U	0.000000		
5*	Standard	45420	-24.660000	1.000000	BAFN10	3.125000 U	0.000000		
6*	Standard		4.240000	2.000000	SF10	3.125000 U	0.000000		
7*	Standard		11.250000	65.125000		3.125000 U	0.000000		
8*	Standard	45105	435.850000	4.000000	SF10	20.000000 U	0.000000		
9*	Standard		36.730000	12.070000	BAFN10	20.000000 U	0.000000		
10*	Standard		-53.760000	20.000000		20.000000 U	0.000000		
STO	Standard		Infinity	0.000000		3.900000 U	0.000000		
12*	Standard	45218	37.330000	14.460000	SK11	20.000000 U	0.000000		
13*	Standard		-31.540000	3.000000	SF5	20.000000 U	0.000000		
14*	Standard		-124.510000	45.319328 V		20.000000 U	0.000000		



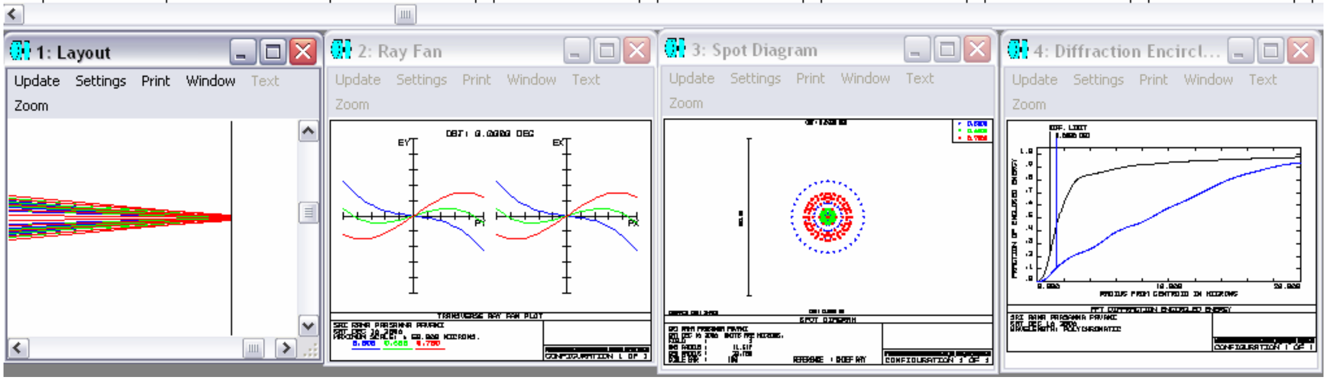
Note that every time we reduce the stop size, we also optimize the system.

Chromatic aberration:

We now compare the "chromaticity" of the system as the system is stopped down

Stop diameter: 10mm

	Surf:Type	Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 0(unused)
OBJ	Standard	OBJECT AT INF	Infinity	Infinity		0.000000	0.000000	
1	Standard	BEFORE LENS	Infinity	50.000000		1.000000 U	0.000000	
2*	Standard	45105	53.760000	12.070000	BAFN10	20.000000 U	0.000000	
3*	Standard		-36.730000	4.000000	SF10	20.000000 U	0.000000	
4*	Standard		-435.850000	0.000000		20.000000 U	0.000000	
5*	Standard	45420	-24.660000	1.000000	BAFN10	3.125000 U	0.000000	
6*	Standard		4.240000	2.000000	SF10	3.125000 U	0.000000	
7*	Standard		11.250000	65.125000		3.125000 U	0.000000	
8*	Standard	45105	435.850000	4.000000	SF10	20.000000 U	0.000000	
9*	Standard		36.730000	12.070000	BAFN10	20.000000 U	0.000000	
10*	Standard		-53.760000	20.000000		20.000000 U	0.000000	
STO	Standard		Infinity	0.000000		5.000000 U	0.000000	
12*	Standard	45218	37.330000	14.460000	SK11	20.000000 U	0.000000	
13*	Standard		-31.540000	3.000000	SF5	20.000000 U	0.000000	
14*	Standard		-124.510000	45.439148 V		20.000000 U	0.000000	



Stop diameter: 6mm

Lens Data Editor

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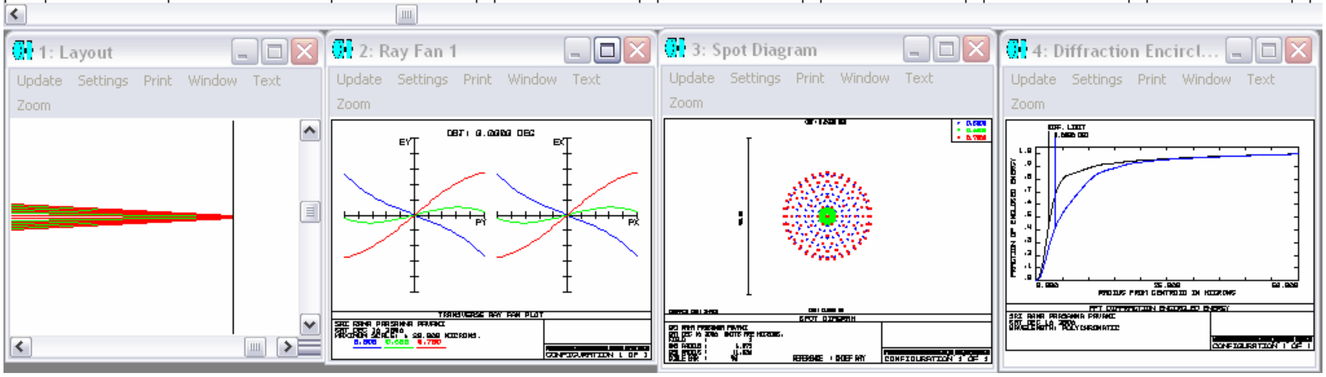
	Surf:Type	Comment	Radius		Thickness		Glass		Semi-Diameter		Conic	Par 0(unused)
OBJ	Standard	OBJECT AT INF	Infinity		Infinity				0.000000		0.000000	
1	Standard	BEFORE LENS	Infinity		50.000000				1.000000	U	0.000000	
2*	Standard	45105	53.760000		12.070000		BAFN10		20.000000	U	0.000000	
3*	Standard		-36.730000		4.000000		SF10		20.000000	U	0.000000	
4*	Standard		-435.850000		0.000000				20.000000	U	0.000000	
5*	Standard	45420	-24.660000		1.000000		BAFN10		3.125000	U	0.000000	
6*	Standard		4.240000		2.000000		SF10		3.125000	U	0.000000	
7*	Standard		11.250000		65.125000				3.125000	U	0.000000	
8*	Standard	45105	435.850000		4.000000		SF10		20.000000	U	0.000000	
9*	Standard		36.730000		12.070000		BAFN10		20.000000	U	0.000000	
10*	Standard		-53.760000		20.000000				20.000000	U	0.000000	
STO	Standard		Infinity		0.000000				3.000000	U	0.000000	
12*	Standard	45218	37.330000		14.460000		SK11		20.000000	U	0.000000	
13*	Standard		-31.540000		3.000000		SF5		20.000000	U	0.000000	
14*	Standard		-124.510000		45.502971	V			20.000000	U	0.000000	



Stop diameter: 10mm

5: Ray Fan 2

Update Settings Print Window

```
Tangential fan, field number 1 = 0.0000 deg

 Pupil        0.5000       0.6000       0.7000
-1.000       22.6999       4.6846     -11.8818
-0.950       20.0078       2.7494     -13.0560
```

Stop diameter: 6mm

6: Ray Fan 3

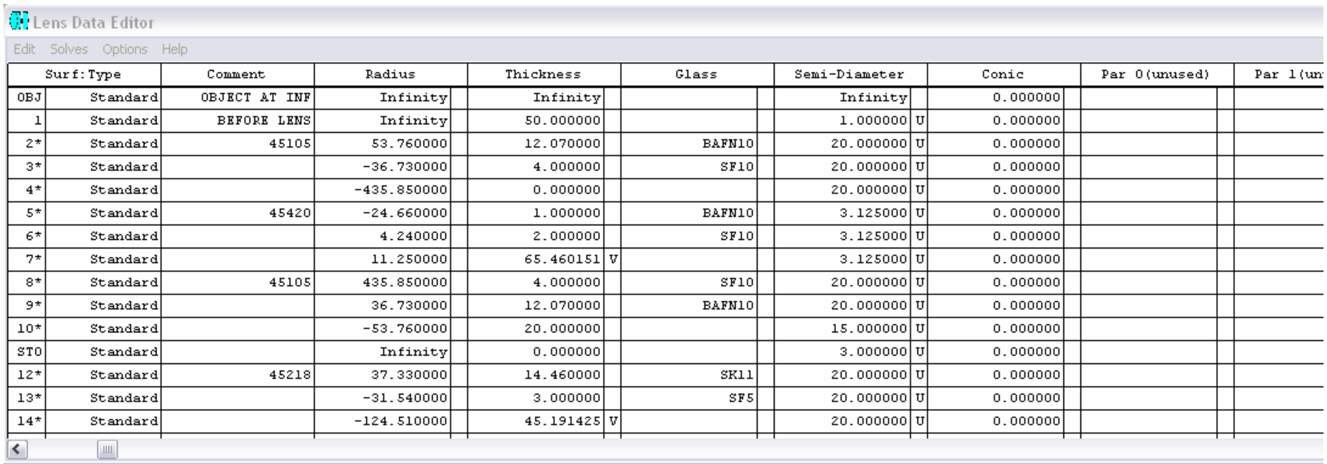
Update Settings Print Window

```
Tangential fan, field number 1 = 0.0000 deg

 Pupil        0.5000       0.6000       0.7000
-1.000       10.5783      -0.8171     -11.0364
```

Despite the use of achromatic lenses, the system is still chromatic to some extent. This is because achromatic lenses are typically corrected only for two different wavelengths, and not through out the spectrum. Nevertheless, had it not been for these achromatic lenses, the chromatic aberration would have been worse. Also, it can be seen that the chromatic aberration varies with stop size too. As the stop size is decreased from 10mm to 6mm, the difference in the max SA of neighboring wavelengths decrease. (Please see the ray fan data)

The off axis performance of the system will be analyzed now. Since we are assuming infinite conjugates, the field is represented in terms of angles (not object height!). In the following example, field angles 0, 0.5, and 1 degrees have been chosen. At the first look these angles might appear really small, but it's important to remember that even small angled rays expand out as they reach infinity. Specifically, the length spanned by a ray at an angle theta after passing through a distance (on axis projection) of z is ztan(theta). Even though tan(theta) is small, z is very large.



Lens Data Editor

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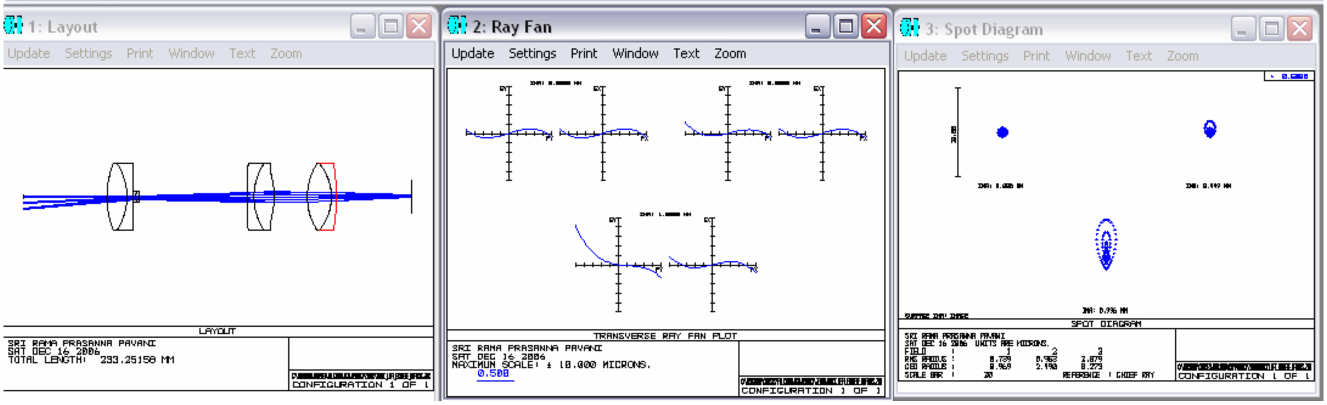
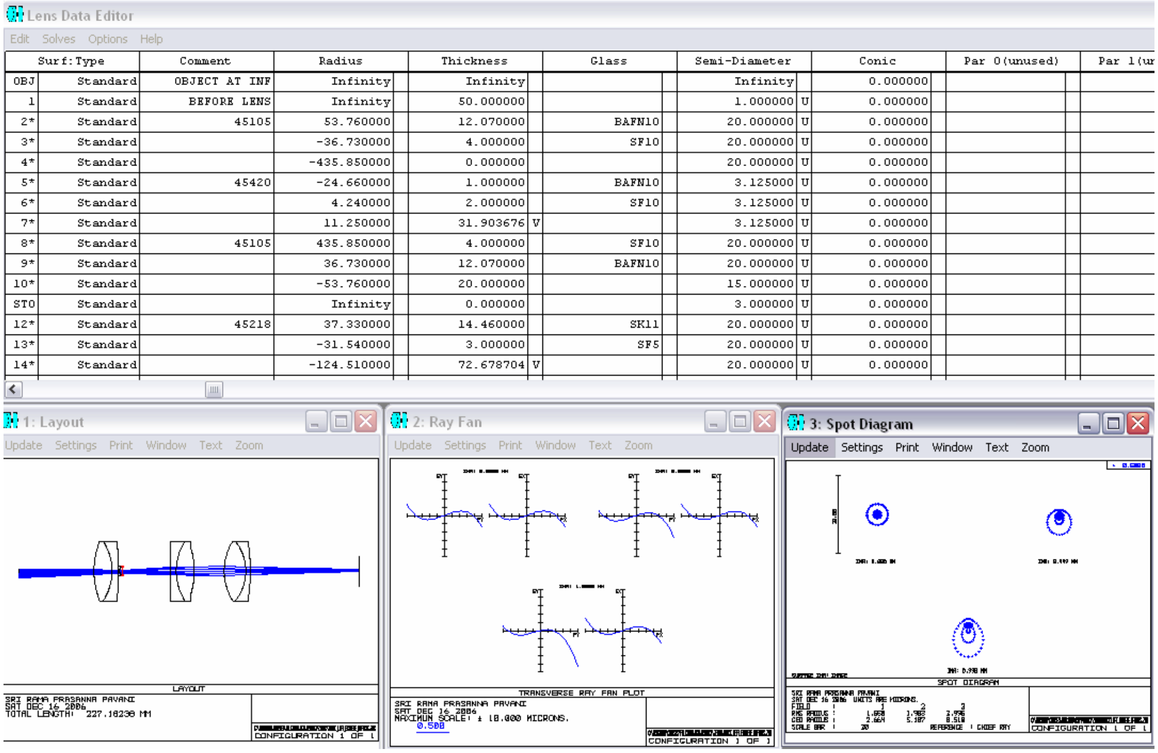
	Surf:Type	Comment	Radius		Thickness		Glass		Semi-Diameter		Conic		Par 0(unused)		Par 1(un
OBJ	Standard	OBJECT AT INF	Infinity		Infinity				Infinity		0.000000				
1	Standard	BEFORE LENS	Infinity		50.000000				1.000000	U	0.000000				
2*	Standard	45105	53.760000		12.070000		BAFN10		20.000000	U	0.000000				
3*	Standard		-36.730000		4.000000		SF10		20.000000	U	0.000000				
4*	Standard		-435.850000		0.000000				20.000000	U	0.000000				
5*	Standard	45420	-24.660000		1.000000		BAFN10		3.125000	U	0.000000				
6*	Standard		4.240000		2.000000		SF10		3.125000	U	0.000000				
7*	Standard		11.250000		65.460151	V			3.125000	U	0.000000				
8*	Standard	45105	435.850000		4.000000		SF10		20.000000	U	0.000000				
9*	Standard		36.730000		12.070000		BAFN10		20.000000	U	0.000000				
10*	Standard		-53.760000		20.000000				15.000000	U	0.000000				
STO	Standard		Infinity		0.000000				3.000000	U	0.000000				
12*	Standard	45218	37.330000		14.460000		SK11		20.000000	U	0.000000				
13*	Standard		-31.540000		3.000000		SF5		20.000000	U	0.000000				
14*	Standard		-124.510000		45.191425	V			20.000000	U	0.000000				



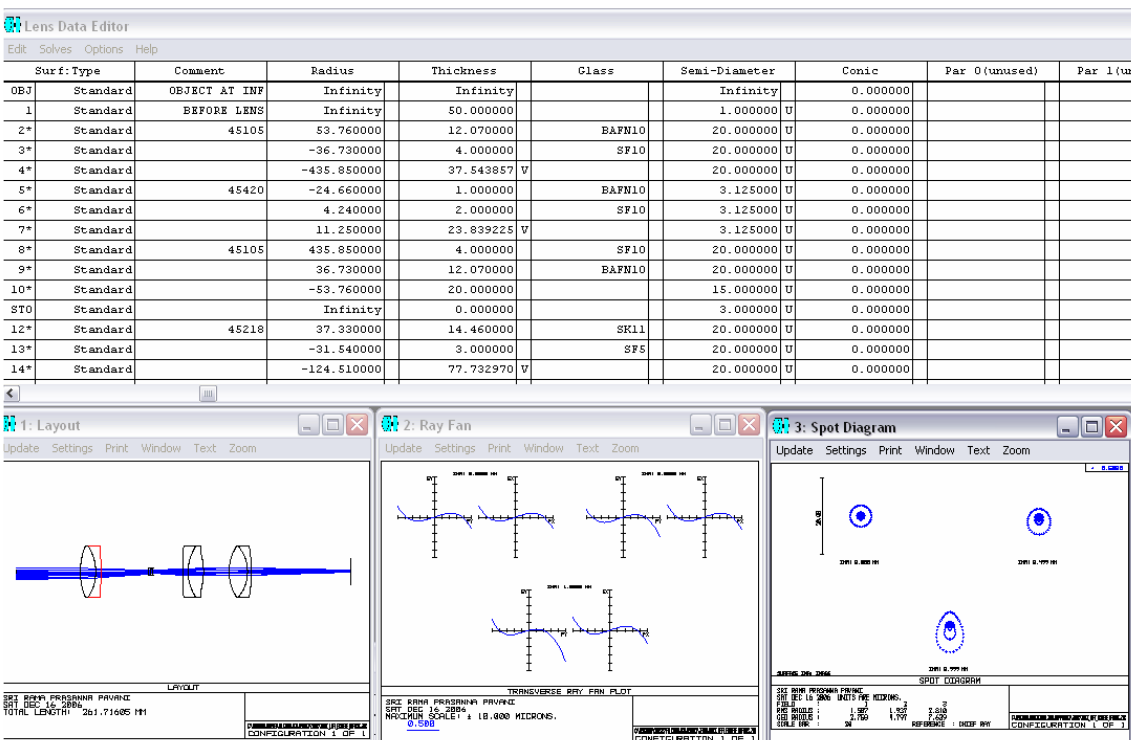
The onaxis point suffers only from spherical aberration, while the off axis points are plagued by coma (The comet tail can be clearly seen in the spot diagram). Since we need a reasonable performance through out the field of view, we now would like to optimize our system so as to reduce off axis aberrations. As we have already decided not to make custom designed lenses (expensive!), the degrees of freedom we have at this point are the distances. The obvious way of reducing offaxis aberrations is by restricting the field of view (angular, in our case). But, that would be the last resort when we have explored all other possibilities.

To start with, let's optimize distances. First, the image plane distance and the distance between the two positive lenses of the zoom lens are specified as variable parameters.



Surf	Type	Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 0(unused)	Par 1(un
OBJ	Standard	OBJECT AT INF	Infinity	Infinity		Infinity	0.000000		
1	Standard	BEFORE LENS	Infinity	50.000000		1.000000 U	0.000000		
2*	Standard	45105	53.760000	12.070000	BAFN10	20.000000 U	0.000000		
3*	Standard		-36.730000	4.000000	SF10	20.000000 U	0.000000		
4*	Standard		-435.850000	0.000000		20.000000 U	0.000000		
5*	Standard	45420	-24.660000	1.000000	BAFN10	3.125000 U	0.000000		
6*	Standard		4.240000	2.000000	SF10	3.125000 U	0.000000		
7*	Standard		11.250000	31.903676 V		3.125000 U	0.000000		
8*	Standard	45105	435.850000	4.000000	SF10	20.000000 U	0.000000		
9*	Standard		36.730000	12.070000	BAFN10	20.000000 U	0.000000		
10*	Standard		-53.760000	20.000000		15.000000 U	0.000000		
STO	Standard		Infinity	0.000000		3.000000 U	0.000000		
12*	Standard	45218	37.330000	14.460000	SK11	20.000000 U	0.000000		
13*	Standard		-31.540000	3.000000	SF5	20.000000 U	0.000000		
14*	Standard		-124.510000	72.678704 V		20.000000 U	0.000000		

The coma seems to have shifted from one direction to another and the on axis spot is more aberrated than before! Reject this! We now optimize over image, f2, and f3 lens distances.



Surf	Type	Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 0(unused)	Par 1(un
OBJ	Standard	OBJECT AT INF	Infinity	Infinity		Infinity	0.000000		
1	Standard	BEFORE LENS	Infinity	50.000000		1.000000 U	0.000000		
2*	Standard	45105	53.760000	12.070000	BAFN10	20.000000 U	0.000000		
3*	Standard		-36.730000	4.000000	SF10	20.000000 U	0.000000		
4*	Standard		-435.850000	37.543857 V		20.000000 U	0.000000		
5*	Standard	45420	-24.660000	1.000000	BAFN10	3.125000 U	0.000000		
6*	Standard		4.240000	2.000000	SF10	3.125000 U	0.000000		
7*	Standard		11.250000	23.839225 V		3.125000 U	0.000000		
8*	Standard	45105	435.850000	4.000000	SF10	20.000000 U	0.000000		
9*	Standard		36.730000	12.070000	BAFN10	20.000000 U	0.000000		
10*	Standard		-53.760000	20.000000		15.000000 U	0.000000		
STO	Standard		Infinity	0.000000		3.000000 U	0.000000		
12*	Standard	45218	37.330000	14.460000	SK11	20.000000 U	0.000000		
13*	Standard		-31.540000	3.000000	SF5	20.000000 U	0.000000		
14*	Standard		-124.510000	77.732970 V		20.000000 U	0.000000		

There's a problem. Optimizing over three different distances has changed the zoom! We want to optimize the system at its mimimum zoom configuration (negative lens in its left extreme position). We'd consider other zoom locations a little later. Because of this reason, we reject the idea of optimizing over three distances. In order to get back to the diffraction limit, we'll have to stop down the aperture a little bit, and also reduce the field angle a bit.

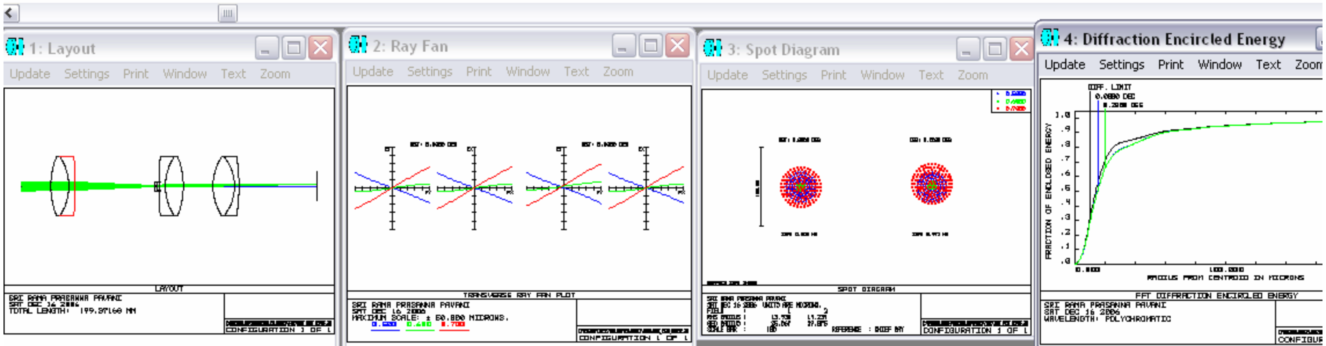
We are now done with the aberration analysis for one zoom position. The same can be done for other zoom positions too. Strictly speaking, optimization over image plane distance at every zoom location would give non-identical results for best possible system configuration. But note that the image plane distance is a constant. (we don't have any mechanical compensation in the camera subsystem). Hence the best we could do is to figure out the optimum image plane distance in the middle of the zoom range. On the other hand, optimization over F1 distance is good. It's good because F1 distance can be dynamically varied for different values of zoom.

In the following few pages, aberration analysis for other zoom locations will be performed.

Negative lens at its right extreme location (maximum zoom)

Lens Data Editor

	Surf:Type	Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 0(unused)	Par 1(unused)
OBJ	Standard	OBJECT AT INF	Infinity	Infinity		Infinity	0.000000		
1	Standard	BEFORE LENS	Infinity	20.000000		0.000000 U	0.000000		
STO	Standard		Infinity	0.000000		3.000000 U	0.000000		
3*	Standard	45105	53.760000	12.070000	BAFN10	20.000000 U	0.000000		
4*	Standard		-36.730000	4.000000	SF10	20.000000 U	0.000000		
5*	Standard		-435.850000	54.014723 V		20.000000 U	0.000000		
6*	Standard	45420	-24.660000	1.000000	BAFN10	3.125000 U	0.000000		
7*	Standard		4.240000	2.000000	SF10	3.125000 U	0.000000		
8*	Standard		11.250000	0.000000		3.125000 U	0.000000		
9*	Standard	45105	435.850000	4.000000	SF10	20.000000 U	0.000000		
10*	Standard		36.730000	12.070000	BAFN10	20.000000 U	0.000000		
11*	Standard		-53.760000	20.000000		20.000000 U	0.000000		
12*	Standard	45218	37.330000	14.460000	SK11	20.000000 U	0.000000		
13*	Standard		-31.540000	3.000000	SF5	20.000000 U	0.000000		
14*	Standard		-124.510000	52.756962		20.000000 U	0.000000		
IMA	Standard	IMAGE	Infinity			10.000000 U	0.000000		



5: Ray Fan 2

Tangential fan, field number 1 = 0.0000 deg

Pupil	0.5000	0.6000	0.7000
-1.000	18.3639	-4.5390	-25.0671
-0.950	17.2711	-4.5306	-24.0535
-0.900	16.2050	-4.4887	-23.0030

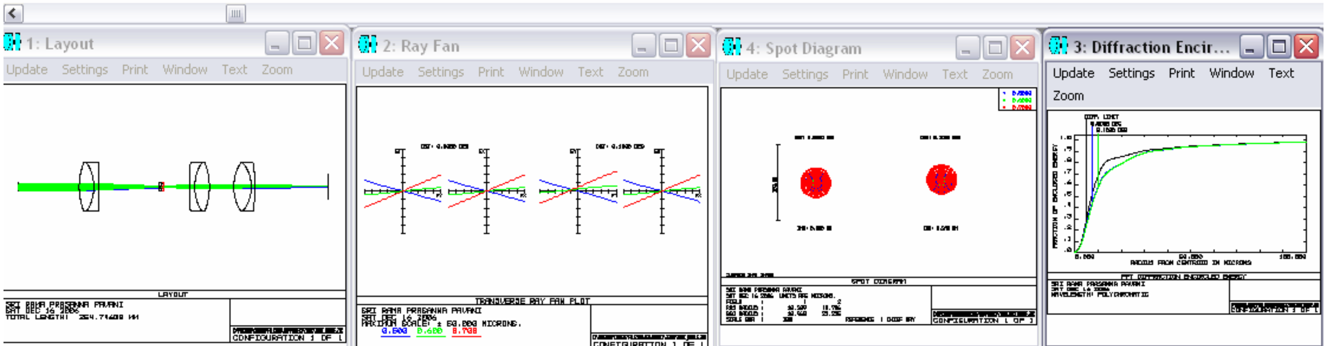
We have ~diffraction limited performance for offaxis (0.5degree) angle and for all three colors (0.5, 0.6,and 0.7um)

Negative lens somewhere in between the two positive lens (middle of the zoom range)

Lens Data Editor

Edit Solves Options Help

Surf	Type	Comment	Radius	Thickness	Glass	Semi-Diameter	Conic	Par 0(unused)	Par 1(unused)
OBJ	Standard	OBJECT AT INF	Infinity	Infinity		Infinity	0.000000		
STO	Standard	BEFORE LENS	Infinity	50.000000		3.000000 U	0.000000		
2*	Standard	45105	53.760000	12.070000	BAFN10	20.000000 U	0.000000		
3*	Standard		-36.730000	4.000000	SF10	20.000000 U	0.000000		
4*	Standard		-435.850000	50.000000		20.000000 U	0.000000		
5	Standard		Infinity	0.000000		0.909228	0.000000		
6*	Standard	45420	-24.660000	1.000000	BAFN10	3.125000 U	0.000000		
7*	Standard		4.240000	2.000000	SF10	3.125000 U	0.000000		
8*	Standard		11.250000	22.011293		3.125000 U	0.000000		
9*	Standard	45105	435.850000	4.000000	SF10	20.000000 U	0.000000		
10*	Standard		36.730000	12.070000	BAFN10	20.000000 U	0.000000		
11*	Standard		-53.760000	20.000000		20.000000 U	0.000000		
12*	Standard	45218	37.330000	14.460000	SK11	20.000000 U	0.000000		
13*	Standard		-31.540000	3.000000	SF5	20.000000 U	0.000000		
14*	Standard		-124.510000	60.134790 V		20.000000 U	0.000000		
IMA	Standard	IMAGE	Infinity			10.000000 U	0.000000		



5: Ray Fan 2

Update Settings Print Window

Tangential fan, field number 1 = 0.0000 deg

Pupil	0.5000	0.6000	0.7000
-1.000	12.9223	-4.2261	-18.9596

We have ~diffraction limited performance for offaxis (0.5degree) angle and for all three colors (0.5, 0.6,and 0.7um)

3. Conclusion

In section 1, we analyzed the need-based evolution of the camera. Later, we went on to design a contemporary digital camera. Ray sketches, paraxial designs were analyzed and the most suitable design was chosen. Finally, ZEMAX was used to characterize the aberrations and also to optimize the system. At this point, we are well equipped (with results) to answer the questions raised in the first page.

- **Is a digital camera <u>really</u> better that a film camera?**
  Yes! It permits easy post processing. The resolution of a typical film is much higher than a contemporary CCD detector. As we saw earlier, the resolution of a camera is primarily dependent on the NA of the system. That's not to say that detector resolution is unimportant. For avoiding aliasing, the detector pixel spatial frequency should always be greater than twice the spatial frequency of the field (Nyquist).

- **Why is a "good" camera expensive?**
  As we noted, cost increases as F/# decreases. Also, multi element lenses are required for aberration correction.

- **1, 2, 3,..10 Mega pixels... Does this "number" have a fundamental limit?**
  Yes, there's not much point in increasing the number of pixels beyond nyquist. A slight over sampling is considered good. But, over sampling by anything more than a factor of 2 is a over kill! Since all cameras have a limited field of view (to minimize off axis aberrations) [we faced this problem too!], the detector dimensions cannot be made arbitrarily large.

- **F/#, NA, DOF, Resolution, Focal length, #Mega Pixels. Why so many parameters?**
  At this point, it should (hopefully) be clear that all of these parameters are interdependent. They all depend on these fundamental parameters: image/object distances, lens parameters like n,Cs,ds, etc. If they are all functions of the same variables, why have them at all? Well, consider the following: Diamond, graphite, and charcoal. They all are made only of carbon (with different lattice structures and densities, of course!) How would it sound if one were to go to a jeweler and ask for a carbon crystal arranged in a cubic bravais lattice structure with density 3.52?? Quite similarly, F/#, NA, DOF, etc are used to characterize various important features of a camera. For example, F/# represents the speed of a camera. DOF determines how far objects can be displaced in z, and yet be imaged in focus. Interdependent parameters may sometimes appear redundant, but a deeper look would reveal the immense convenience they offer during analysis.

- **Why don't ultra high resolution cameras have a long depth of field?**
  Resolving power is proportional to NA, while DOF is inversely proportional to the square of NA.

- **Why aren't monochrome cameras extinct?**
  We didn't talk about this at all in the project, as the answer to this question has nothing to do with system design. Nevertheless, color ccd detectors typically are configured using what's commonly known as bayer pixel arrangement. In essence, a color ccd detector has R, G, and B pixels periodically arranged. The post processing typically results in loss of resolution, as it involves averaging in space (low pass filtering). Hence, unless the system is highly oversampled, it's not advisable to use color ccd detectors.

- **Why can a camera zoom in/out when our eyes cannot?**
  Zoom lenses can dynamically vary their effective focal lenses and yet be in focus. This is typically achieved by mechanical compensation. Our eye lens can change its focal length too, but there's no system in place for mechanical compensation.

- **What is all this hype about SLR cameras?**
  The view finders in SLR cameras see through the main lens used for imaging, and hence there can be no transverse displacement between the image that's seen through the view finder and the image that's recorded. LCD panels in modern digital cameras could potentially eradicate SLR cameras.

- **Can a "passive" camera capture the 3^{rd} spatial dimension?**
  Yes. PSF of an imaging system varies with defocus. Passive 3D cameras typically alter the imaging system in order to control the variation of psf with defocus in a controlled/desirable

way. These cameras are come under the category of computational imaging systems, where ~half of the work is done in optics and the other half is accomplished with signal processing.

- **Are two successive images of the same object identical?**
  No. Detector (digital) noise varies with time, as noise (Ex: shot) is a random function generally with a well defined probability distribution function (For shot, it's poissonian). The reason for the randomness is because of the uncertainty in the arrival time of a photon. Films suffer from grain noise.

4. Acknowledgements

http://moisl.colorado.edu http://cdm-optics.com

5. References

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6. Appendix - MATLAB code

Function used for raytracing

```
% Paraxial ray tracing through many surfaces. Mouroulis 4.1
%
% INPUTS:
% c      - array of curvatures
% d      - array of distances
% n      - array of refractive indices
% h_next - initial height
% u_next - initial angle
%
% OUTPUTS:
% h_next - final height
% u_next - initial height
%
% Sri Rama Prasanna Pavani <pavani@colorado.edu>
function [h_next, u_next] = raytrace(c, d, n, h_next, u_next)

% sanity check!
if (nargin ~= 5 || length(c) ~= length(d) || length(n) ~= length(c) + 1)
    error('Incorrect argument list!');
end

for ii = length(c)
    u_next = (-h_next * c(ii) * (n(ii+1) - n(ii)) + n(ii) * u_next)/n(ii+1);
    h_next = h_next + d(ii) * u_next;
end
```

Function to calculate throw and zoom:

```
% calculates the eff. focal length F, throw, and zoom based on f1 and f2
% @author: pavani@colorado.edu
function [] = spec(f1,f2)

if nargin == 0,
f1 = 10;
f2 = -4;
end


f3 = 6;
F = (f1 * f2)/(f1 + f2)
throw = f1 - abs(F) + f3

% define zoom as the maximum magnification possible example: 6x
m1 = -F/f1;
zoom = 1./m1
```

Effective focal length:

```
% effective focal length plots
% @author: pavani@colorado.edu

f1 = linspace(1,10,50); f2 = -f1;
len = length(f1);

for ii = 1:len
```

```
    for jj = 1:len
        F(ii,jj) = (f1(ii) * f2(jj))/(f1(ii) + f2(jj));
    end
end

imagesc(f1,f2,F); cmg;cb;
xlabel('f1 (cm) ');
ylabel('f2 (cm)');
zlabel('eff. focal length (cm)');
title('eff. focal length')

%power
figure;
imagesc(f1,f2,1./F); cmg;cb;
xlabel('f1 (cm) ');
ylabel('f2 (cm)');
zlabel('power (cm^-1)');
title('power')
```

Zoom and throw plots:

```
% Zoom and throw plots
% @author: pavani@colorado.edu

f1 = linspace(1,10,50);
f2 = -f1;

len = length(f1);

for ii = 1:len
    for jj = 1:len
        F(ii,jj) = (f1(ii) * f2(jj))/(f1(ii) + f2(jj));
    end
end

imagesc(f1,f2,F); cmg;cb;
xlabel('f1 (cm) ');
ylabel('f2 (cm)');
zlabel('eff. focal length (cm)');
title('eff. focal length')

%power
figure;
imagesc(f1,f2,1./F); cmg;cb;
xlabel('f1 (cm) ');
ylabel('f2 (cm)');
zlabel('power (cm^-1)');
title('power')
f1 = linspace(1,10,100);
f2 = -f1;
len = length(f1);

%Assume
f3 = 6;

throw = zeros(len);
zoom = zeros(len);
for ii = 1:len
```

```
    for jj = 1:len

       if (-(f2(jj)) < 0.5*f1(ii))
         F = (f1(ii) * f2(jj))/(f1(ii) + f2(jj));
        throw(ii,jj) = abs(F) + f1(ii) + f3;

        % define zoom as the maximum magnification possible example: 6x
        F = (f1(ii) * f2(jj))/(f1(ii) + f2(jj));
        m1 = -F/f1(ii);
        zoom(ii,jj) = 1./m1 ;

    end
    end
end

mesh(f2,f1,zoom); cmg;
xlabel('f2 (cm) ');
ylabel('f1 (cm)');
zlabel('zoom ');
title('Zoom vs focal lengths f1 and f2')

figure;
mesh(f2, f1, throw); cmg;
xlabel('f2 (cm) ');
ylabel('f1 (cm)');
zlabel('throw (cm) ');
title('Throw vs focal lengths f1 and f2')
```

Cost vs d1,d2 plots

```
% cost vs d1, d2 plots
% @author: pavani@colorado.edu

d1 = linspace(1,10,100);
d2 = -d1;
len = length(d1);
k = 2;

cost = zeros(len);
for ii = 1:len
    for jj = 1:len

        cost(ii,jj) = k*d1(ii) + k*d2(jj);

    end
    end
end


figure;
mesh(d2, d1, cost); cmg;
xlabel('d2 (cm) ');
ylabel('d1 (cm)');
zlabel('cost ($) (arbitraty scale)');
title('Cost vs d1 and d2')
```