

# Astronomical Observing Techniques – Optical Design

15 October 2013

**Important notes:** These exercises need the optical design program ZEMAX<sup>®</sup>. It is installed on the PC in room 421, which also controls the white board. To run the program a USB hardware key is needed.

Deadline for the homework is **7 Nov. 2013**. There will be two items to return: first, the answers to the questions in the below step-by-step instructions, and, second, the two \*.zmx files from exercises 2 and 3, which include your designed systems. Please put the sheet in Stephanie's mailbox ("pigeon hole") and email the files to heikamp@strw.leidenuniv.nl. Please choose unique file name, e.g. your last name and the exercise number.

## Exercise 1

Set up the system as described in the short "Introduction to ZEMAX<sup>®</sup>" Manual and perform the same image analysis as described there. This is only a training exercise (nothing to hand in) to familiarize yourself with the program.

## Exercise 2

We want to design a "simple" high resolution near-infrared camera for (a simplified version of) ESO's VLT. We choose the following design parameters:

- Maximum field of view (FOV): 1 arcmin
- Refractive optics (only lenses)
- Wavelengths: the center wavelengths of the near-IR J, H, and K-bands

### **Step 1:** "Simulating" the telescope optics

For simplicity we only want to set up the optics of our camera, and not to design the telescope. However we need to calculate the properties of the incoming rays as if they were coming from the VLT and produce a focused image on the object plane of our camera. For this first step we do not need ZEMAX<sup>®</sup> but only the simple equations from our lecture on telescopes.

The VLT has an aperture size of 8.2m and, at the Nasmyth focus, an F-number of 15. Calculate the object height (in the image plane of telescope) for the maximum FOV. Calculate the numerical aperture (N.A.) in the object plane (i.e., rays from the telescope). List both numbers here:

Object height [mm] = \_\_\_\_\_

N.A. [degrees] = \_\_\_\_\_

**Step 2:** Setting up a ZEMAX<sup>®</sup> basic system

Open a new lens file. Remember that we do not want to simulate the telescope. Hence, the three default surfaces correspond to the object plane, pupil stop and image plane of our (yet to be designed) camera. To avoid error messages (our camera has only finite length!), reduce the 'Thickness' of the 'Object' from 'Infinity' to a finite, arbitrary value, e.g. 1 meter.

Now we have to define the incoming rays onto our 'Object' plane as if they were coming from the telescope. Open the system's *General* dialog box to define the aperture type via the NA calculated above. Then open the *Field Data* dialog box and enter three field points (our system shall be rotationally symmetric and we only need field points in the Y-direction). Choose one on the optical axis, one at the maximum object height (step 1) and one at 70% of the maximum object height. Finally, open the *Wavelength Data* dialog box and enter the three nominal wavelengths. Check the current optical layout by plotting the 2D Layout. Describe in a few words:

What is the left surface? \_\_\_\_\_

What is the right surface? \_\_\_\_\_

**Step 3:** Add two lenses to focus the image onto our image plane

Now we want to create an image, which requires some focusing optics. Insert one lens between the Object and the pupil stop, and one lens between the pupil stop and the Image. Choose the infrared transmissive CaF<sub>2</sub> for the lens material. Make both lenses bi-convex by adding a small curvature of 200mm to each surface. Add distances of 100mm between the lenses and the Object, the pupil stop and the Image, respectively. Make the lenses each 10mm thick. Check the current optical layout by plotting the 2D Layout. Describe in a few words:

How does it look now? \_\_\_\_\_

\_\_\_\_\_

**Step 4:** Focus the simple setup

To focus this basic setup we first create the default Merit Function (Editor → Merit Function → Tools → Default Merit Function). Choose RMS Spot Radius, and include Glass Thickness Boundary values of 2 (Min), 15 (Max) and 2 (Edge). We also define the Air Thickness Boundary values as 5, 1000, and 5, respectively. For now, we choose only one parameter for optimization, namely the focus, i.e. the Thickness of the second last surface. Now we run the 'Automatic' optimization and check the 2D Layout and the Lens Data Editor.

What is now the distance to the image plane? \_\_\_\_\_

What is the height of the image [mm]? \_\_\_\_\_

**Step 5:** Matching the camera to a detector.

Our camera shall be equipped with a  $1024 \times 1024$  pixel detector on which the full FOV has to fit. One pixel is  $30\mu\text{m} \times 30\mu\text{m}$  in size.

What is the size of the detector? \_\_\_\_\_

What should thus be the magnification of the camera optics? \_\_\_\_\_

**Step 6:** Optimizing the system to meet the required magnification

To adjust the magnification we need to do two things: First, we need to allow for additional free parameters in the optimization. We make the front and back surfaces of the 2<sup>nd</sup> lens variable, and we allow for a variable distance between the 1<sup>st</sup> lens and the pupil stop and between the pupil stop and the 2<sup>nd</sup> lens. Second, we need to add an entry for the magnification to the Merit Function. Open the Merit Function Editor and Insert Operand. Right-click on the field to open the Optimization Operand dialog box. Choose the operand 'PMAG', set the target value to the desired magnification – note that the value has to have a negative sign since the image is upside down – and give it a strong weight of 2. Rerun the Automatic optimization.

Check the 2D Layout. Does it look o.k.? \_\_\_\_\_

Check the Merit Function: what is the magnification? Is it close to the desired value?

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Check the Spot Diagram. What is the largest RMS spot radius? How does it compare to the pixel size?

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**Step 7:** Fine-tuning the system

Now we want to see if we can further improve the performance by adding another lens. Insert two surfaces after the 2<sup>nd</sup> lens. Make them a bi-convex  $\text{CaF}_2$  lens with radii of 500mm. Make both radii variable. Make the lens 10mm thick and place it 10mm from the 2<sup>nd</sup> lens and 50mm before the detector. Also, make the latter two distances variable. Rerun the Automatic optimization.

What is the worst RMS spot size?

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Our system is being optimized for three wavelengths simultaneously. Assess and describe qualitatively whether or not the chromatic errors are the dominating aberrations.

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So far we have worked with only one lens material (CaF<sub>2</sub>). Usually, the combination of two different glasses (one with higher refractive index and lower dispersion and one with lower refractive index and higher dispersion) reduces chromatic errors. Change the material of the 1<sup>st</sup> and the 3<sup>rd</sup> lens to BaF<sub>2</sub>. Rerun the Automatic optimization.

What is the worst RMS spot size now? Has it improved?

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**We have now reached the final system configuration. This is the file to hand in.**

**Step 8:** Performance analysis

Now we want to analyze the system performance.

Check 'Reports' → 'System Data'. What is the Image Space N.A. ZEMAX<sup>®</sup> calculates for our camera? Is this value in agreement with the N.A. provided by the VLT and the system magnification?

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Compute the Huygens PSF (submenu 'Analysis'). Does the PSF look like an Airy function?

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The menu of the Huygens PSF also provides the wavelength-averaged Strehl ratio. Re-compute the Strehl ratio for only the shortest wavelength (Settings → Wavelength → 1 → OK). Note the Strehl ratio. What is the approximate WFE one would derive from this value (in units of lambda), using the formula from the lecture on diffraction optics?

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Compute the Wavefront Map (submenu 'Analysis'). What is the RMS WFE in units of waves? Does it agree with the previous estimate?

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Compute the Encircled Energy (submenu 'Analysis') using diffraction analysis. At what distance would an ideal diffraction-limited optics include 50% of the energy?

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How does that compare to our actual camera optics? How many detector pixels (1D cut) are needed to encircle 50% of the energy?

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Now we check the distortion of our camera optics (submenu `Analysis` → Miscellaneous → Grid Distortion). Does our optics suffer from barrel or pincushion distortion?

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Now we quantify the distortion (submenu `Analysis` → Miscellaneous → Field Curv/Dist). Change the default settings under `Settings` → Display from Percent to Absolute. What are the distortions corresponding to our two off axis field points? How many detector pixels is that? How does it increase with distance from the optical axis?

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Finally, we check the impact of the pupil size on aberrations. We insert a pupil stop to decrease the size of camera pupil. This can be done in the Lens Data Editor by right-clicking on the Surf:Type field of the STop. In the pop-up window click on the tab `Aperture` and select Aperture Type: Circular Aperture. Enter below a Max Radius which is only half the size of the nominal aperture. Check the 2D Layout to see if it had any effect. Calculate the Spot Diagram and the

How much has the Spot Diagram changed? \_\_\_\_\_

How much has the Encircled Energy changed? \_\_\_\_\_

### Exercise 3

Design your own optical system. The ZEMAX® \*.zmx file should also be handed in.

The system does not have to be complicated but should fulfill some meaningful purpose. State your objective below.

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