Bruno Hiberty
Ecole Supérieure d'Optique
Orsay, France

Improvement of the Instrumentation of the Danish 1.54 m Telescope

Directed by Per Kjærgaard Rasmussen

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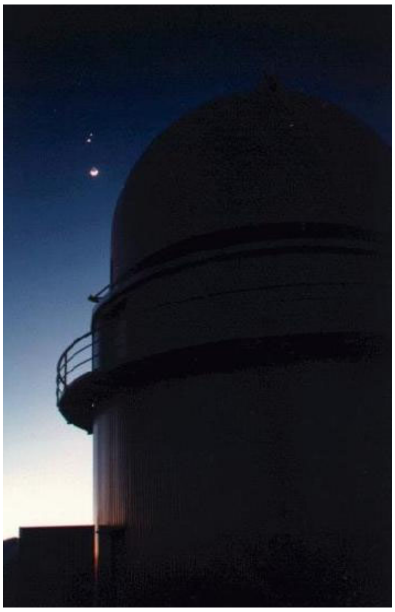


Copenhagen University Astronomical Observatory
Niels Bohr Institute for Astronomy, Physics and Geophysics
Copenhagen, Denmark

Abstract

English

During my training period at the Copenhagen University Observatory, I was in charge of the improvement of the Danish 1.54 m Telescope situated at La Silla, Chile.
I lead a wavefront sensing campaign to measure the optical quality of the telescope and analyzed the results.
I also started the design of a new spectrograph/imager focal reducer and studied numbers of critical issues: the beam separation problem, the design of an UV instrument, ghost analysis and sky concentration calculations.

Francais

Lors de mon stage à l'Observatoire de l'Université de Copenhague, j'ai été chargé de l'amélioration de l'instrumentation du télescope 1.54 m de diamètre situé à La Silla, Chili.
J'ai mené une campagne de mesure de front d'onde pour mesurer la qualité optique du téléscope et analysé les résultats.
J'ai aussi réfléchit à la conception d'un nouveau réducteur de focale spectrographe/imageur et étudié de nombreux points critiques: le problème de la séparation du faisceau, de la construction d'un instrument UV, l'analyse des images parasites et le calcul de la concentration du ciel.

Greetings

I would like to express my grateful thanks to all the members in the Observatory: the welcoming was so warm and the ambience so pleasant.
Many thanks to the persons I worked with: Michael, Anton, Jens...
Finally, I would like to thank particularly the head of the instrumentation group, Johannes, to have accepted me, and my boss, Per, for the patience and comprehension every day.

Contents

Introduction

A telescope, as every optical engineer knows, is composed of mirrors that focus the light on a focal plane. But a telescope is rarely used alone. The astronomers often put an instrument afterwards. This instrument can be a focal reducer or a spectrograph, for measurements in the visible spectra, the infrared or the UV, etc.

The Danish 1.54 m Telescope, situated on La Silla, Chile, is the biggest Danish Telescope. It is currently equipped with a spectrograph/imager focal reducer called DFOSC. The Copenhagen University Observatory is willing to build a successor of the DFOSC in the next months.

For my 3rd year SupOptique training period, I was employed there to start thinking about the design and to study all the different issues of the problem. I also lead a wavefront sensing campaign to measure the optical quality of the telescope.

In this report, I will first make a presentation of the Copenhagen University Observatory, the Danish 1.54 m Telescope and its instrumentation.
Then, I will explain the Korhonen-Hartmann wavefront sensing method and discuss the results we obtained.
Finally, I will describe the different studies I have lead concerning the optical design of the future instrument, namely: the beam separation problem, the UV arm design and the ghost analysis.

Conventions

- **Z** is the optical axis
  Y is the vertical direction oriented to the top
  X is the horizontal direction oriented into the sheet
  Usually, the object is on the **Y**-axis.
  Therefore the **Y-Z** plane is the tangential plane and the **X-Z** plane is the sagittal plane.

  Lengths are in millimeters
  Angles are in degrees
  Wavelengths are in nanometers

  (Except indicated)

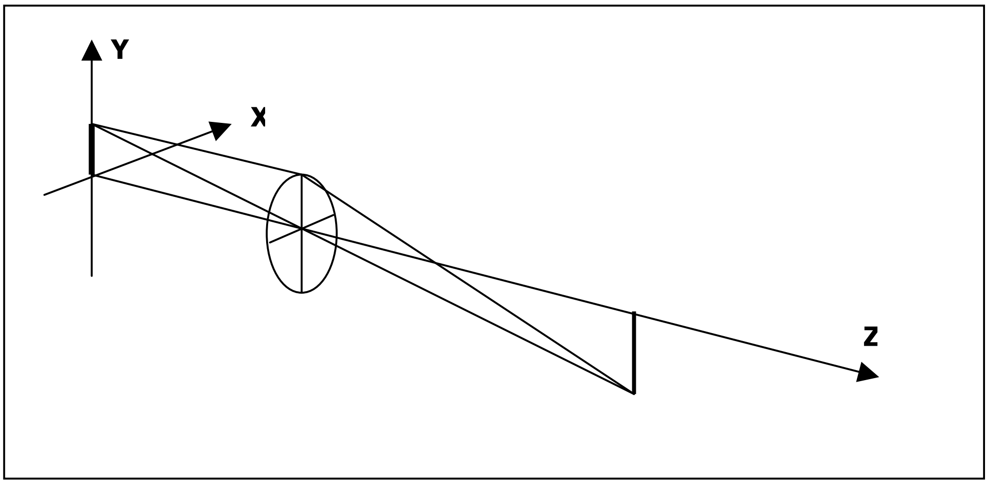


Figure 1: Optical layout convention

- Zernike polynomials used: "Fringe" or "University of Arizona" set (9 first terms here):

Z1= 1	Piston
Z2= $\rho \cos(\phi)$	Tip
Z3= $\rho \sin(\phi)$	Tilt
Z4= $2\rho^2 - 1$	Focus
Z5= $\rho^2 \cos(2\phi)$	3rd order Astigmatism
Z6= $\rho^2 \sin(2\phi)$	3rd order Astigmatism
Z7= $(3\rho^2-2)\rho \cos(\phi)$	3rd order Coma
Z8= $(3\rho^2-2)\rho \sin(\phi)$	3rd order Coma
Z9= $6\rho^4-6\rho^2+1$	3rd order Spherical aberration

…

I- Presentation of the working environment

The Copenhagen University Astronomical Observatory

The Copenhagen University Astronomical Observatory is a group of 25 researchers and 10 technicians constituting the biggest research center in astronomy and astrophysics in Denmark.
It is a part of the famous Niels Bohr Institute for Astronomy, Physics and Geophysics.

The main research topics are:
- Cosmology and extragalactic astronomy
- The structure and evolution of the Milky Way
- Structure and evolution of stars
- Numerical Astrophysics
- Positional astronomy
- IJAF: Telescopes and instrumentation

The Instrumentation Group (IJAF), where I was particularly employed, is in charge of designing, building and maintaining state of the art instruments for telescopes worldwide. It is assisted with electrical, mechanical and software engineers with workshop facilities. Examples of instruments built there are CCD cameras, spectrograph/imager focal reducers and different filter units or adaptators. This group is also responsible for the improvement of the Nordic Optical Telescope, situated in the Canaries Islands and the Danish 1.54 m Telescope situated in Chile.
I worked particularly with Per Kjærgaard Rasmussen, the optical specialist and vice-Director of the group and Michael Andersen from Oulu University Observatory (Finland). I got access to some facilities concerning optics: a rather furnished lab and an optical design program (ZEMAX®).

The Danish 1.54 m Telescope

Overview

The Danish 1.54 m Telescope is, according to its name, a Danish telescope with a diameter of 1.54 m. It is situated on La Silla, Chile, with around 15 other telescopes.
As Denmark is a member of European Southern Observatory (ESO), the observing time is divided between ESO and Danish astronomers.
The telescope was build by Grubb-Parsons and operational in 1979.
The telescope has an off-axis equatorial mount and the optics is of a Ritchey-Chrétien design.
An instrument adaptor is mounted below the mirror cell, and below this is the FASU (Filter And Shutter Unit). The adaptor provides facilities for auto guiding while additional filters can be mounted in the converging beam in FASU.

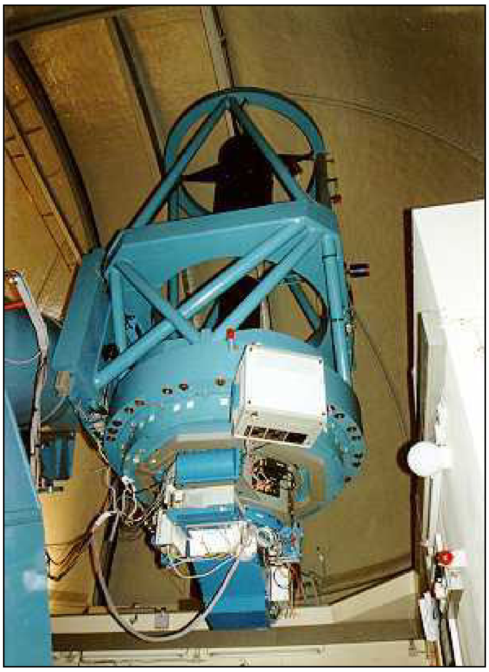


Figure 2: The Danish 1.54 m Telescope

The DFOSC (**Danish Faint Object Spectrograph Camera**) is mounted below the FASU.
This instrument is a spectrograph/imager focal reducer and is the only instrument currently in use on the telescope.

The detector is a 2048 x 2048 pixels CCD camera. The size of a pixel is 15 μm.

Optical Characteristics

Telescope

- Ritchey-Chrétien design
- Diameter: 1.54 m
- Focal length: 13.275 m
- F/D: 8.62
- Obscuration ratio: 0.25

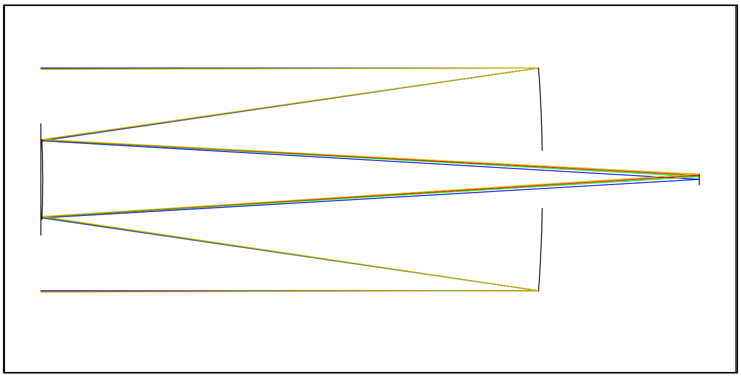


Figure 3: Optical design of Danish 1.54 m Telescope

The DFOSC

DFOSC is focal reducer that can be used as a spectrograph or imager for the visible wavelength domain. It was designed by Bernard Delabre (from ESO) in 1991.

Optical characteristics:
- Reduction ratio: 0.58
- Collimator focal length: 252.1 mm
- Collimator linear field: 52.9 x 52.9 mm
- Camera focal length: 146.3 mm
- Camera linear field: 30.7 x 30.7 mm
- Total length: 719.2 mm

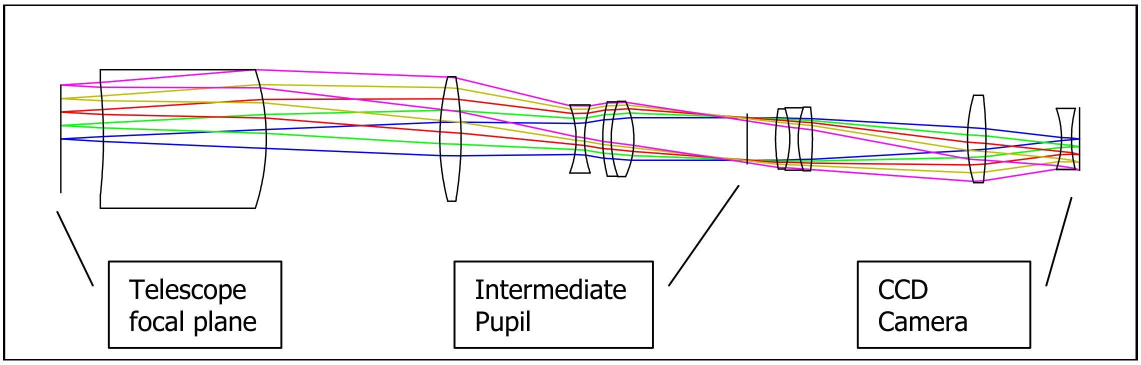


Figure 4: Optical Layout of DFOSC

Nominal values on the Danish 1.54 m telescope:
- Input F/N: 8.6
- Output F/N: 5.0
- Field size: 13'7 x 13'7
- Projected pixel size: 0"403

Optical description of DFOSC

The instrument is divided in two sections: the collimator and the camera.

The collimator creates a parallel beam in the intermediate space having the correct diameter and the sufficient image quality for the spectrographic applications.

The first thick lens is a field lens and places the pupil at the desired position in the intermediate space. In fact, for space reasons, the beam is broken inside this lens with a total internal reflection (all the layouts are drawn straight for clarity). This "lens" is a big prism with 2 lenses stuck on both faces.

The camera gives the final image on the CCD.

In the spectrographic mode, a slit is placed at the telescope focus (on the object) and a grism (a prism + transmission diffraction grating) placed at the intermediate pupil position produces the spectrum on the CCD.
Two wheels allow different slits and different grisms to be used (for different spectral resolution at different wavelengths).
Multi-object spectroscopy is also possible. It requires a specially designed multi-slits plate placed at the telescope focus.
The maximum resolution is R_{max} = 4200.

Another wheel placed just before the grism wheel provides different filters.

Theoretical optical quality on the telescope:

Polychromatic (330-900nm) spot diagram

Field (degrees)	0	0.04	0.08	0.12	0.16
RMS radius (μm)	4.331	3.395	4.610	5.474	12.457
80% encircled energy radius (μm)	7.23	5.91	6.94	8.24	14.09

Others:
Distortion max: 0.25%
Axial color: 200 μm
Lateral color max: 7 μm

We can see that for a field position up to 0.12 degrees (7.2') the optical quality is excellent: the image of one star is completely comprised in one pixel (size 7.5 μm).
The distortion is acceptable for the common applications.

II- Wavefront sensing on D1.54mT

It is always interesting to control the optical quality of a telescope to compare with the theory. The knowledge of the aberrations present in the system can help improving it. Mechanical, optical defaults and misalignments can be fixed this way.
There are many different methods to measure the shape of the wavefront coming out of a telescope. The most used for a telescope in service is probably curvature sensing because it only needs two defocused images. But it requires to unmount the employed instrument and to mount a CCD directly on the telescope. For this reason, wavefront measurements are only possible during technical times. It is important to be able to make a measure at any moment without unmounting the DFOSC.
With the Korhonen-Hartmann method it is possible to include the wavefront sensor inside the DFOSC.
This is the reason why such a wavefront was built and inserted in the DFOSC around 1999.

Principle of Korhonen-Hartmann wavefront sensor

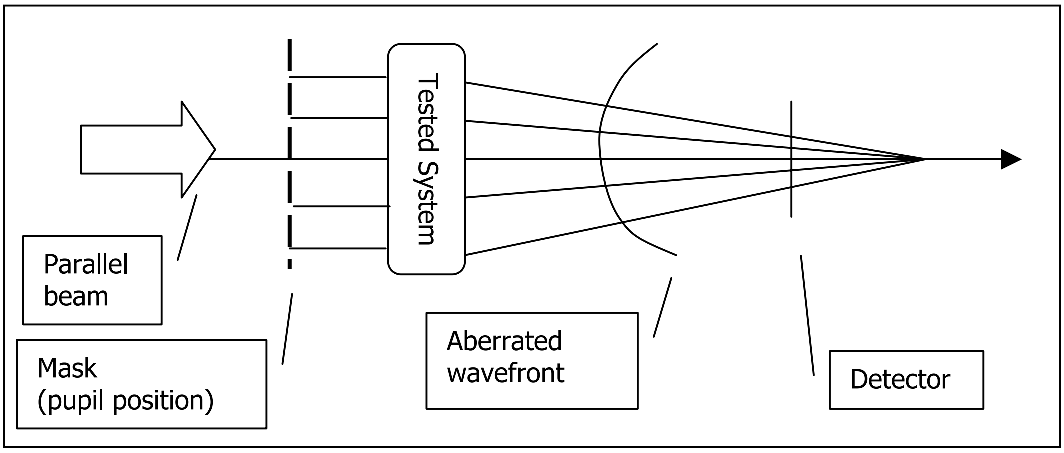
Tapio Korhonen (from Tuorla Observatory, Finland) invented the Korhonen-Hartmann wavefront sensing method in 1984 for the testing of large mirrors during their construction. It is an improvement of the Hartmann technique using interferometry.

Description of the Hartmann technique

The principle of the Hartmann technique is to put a mask with a regular array of holes at the pupil of the system to be tested (here a telescope).
This system is illuminated with a parallel beam and one has to record the position of the spots corresponding to the holes at a defocused position. A phase difference will create a shift of the spot. From the position of the spots it is possible to deduce the shape of the wavefront with the corresponding sampling and then calculate the aberrations of the system.

To measure the position of the spots, the defocus and the separation of the holes has to be quite large in order the spots not to overlap. Therefore the resolution is rather small. Moreover, the image is usually too big to be recorded on a CCD. This is why this technique is rarely used for telescopes.

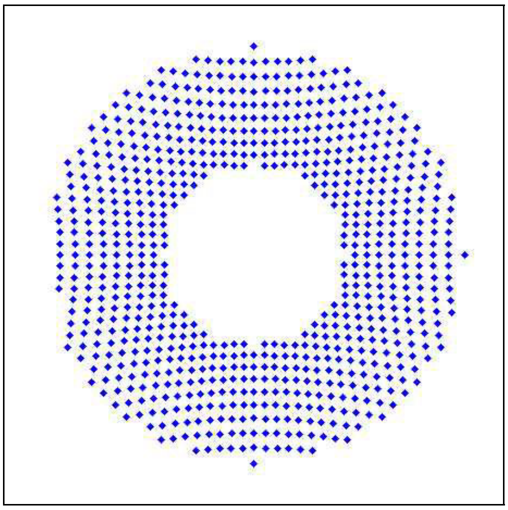
Figure 5: Principle of the Hartmann technique



We made computer simulations of Hartmann test for different aberrations using Zernike phase objects.
(Tilts create a decenter of the image and defocus globally changes the size of the image)

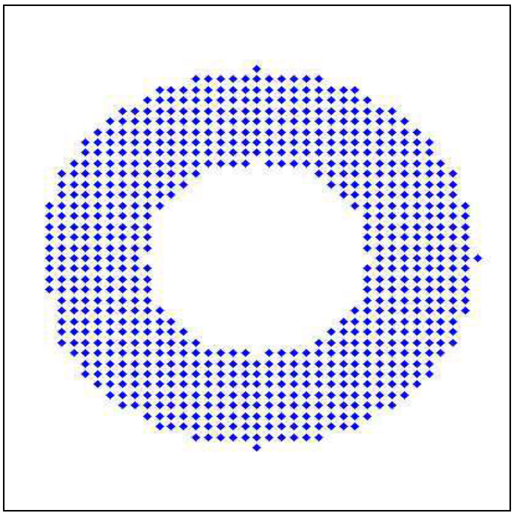
3rd order spherical aberration (Z9= 3):

The spots distributed according to a power 2 radial function.



3rd order astigmatism (Z5= 3):

The figure is elongated in one direction and contracted in the other.



3rd order coma (Z7= 3):

Along one direction, the spots are contracted on one side and elongated on the other.

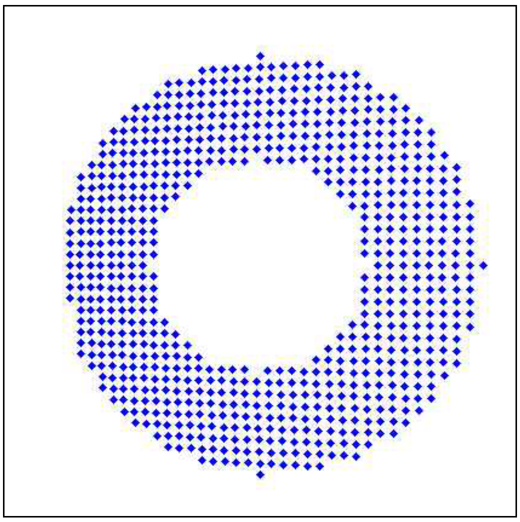


Figure 6: Examples of spot distribution for the Hartmann test and for different optical aberrations

The Korhonen-Hartmann technique

In Korhonen principle, interferences are used. With more spots, and if the image is recorded at a closer focus, the spots will overlap and interfere. At an appropriate defocus, an interference pattern with strong maxima is observed.
The formula below gives the correct focus:

$$\mathbf{S = \lambda\, (f/d)^2}$$

where f is the focal length of the instrument, d the separation between the holes.

A much bigger resolution is then possible, and a CCD can be used since the image is smaller.
Each spot is created by the interference of four holes of the Hartmann mask.
Therefore a 4x4 holes mask would give 9 primary maxima.
The local slope of the wavefront is given by the deviation of the spot compared to the normal position (like in a Hartmann or Shack-Hartmann wavefront sensor).

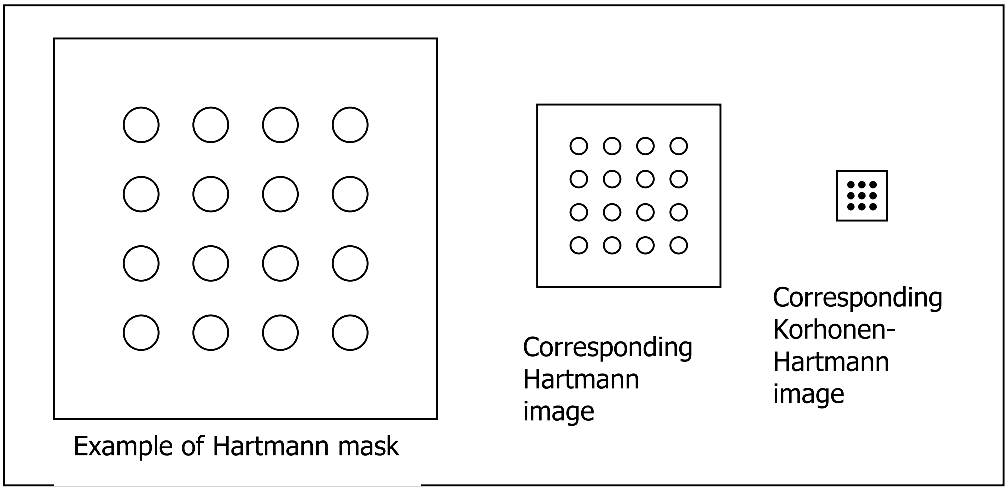


Figure 7: Comparison between Hartmann and Korhonen Hartmann images

Application on the DFOSC

In practice, it is impossible to place a mask on the mirror.
But it is possible to place it at an image of the mirror.
The idea to implement this technique inside the DFOSC is to insert the mask at the intermediate pupil place. The wavefront sensor contains also a convergent lens to create the defocus without need for reconfiguring the DFOSC.

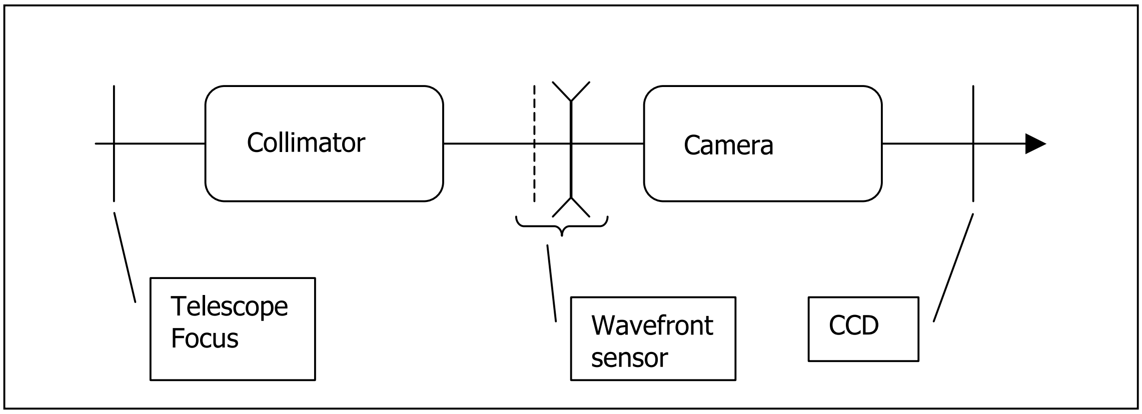


Figure 8: Principle of Korhonen-Hartmann wavefront sensor applied on DFOSC

The wavefront sensor is therefore mounted in the wheel that contains the grisms used for the spectrograph. One just has to turn the wheel on the right position to make a measurement.
Of course, a wavefront measurement will give the wavefront of this complete system:

{telescope}+{DFOSC}+{wavefront sensor}

But a calibration source can be put at the telescope focus, which will give the wavefront of:

{DFOSC}+{wavefront sensor}

Since the optical path difference is additive, the difference between these two measurements gives the telescope wavefront error.
The wavefront is finally decomposed in a sum of Zernike polynomials that form an orthonormal basis for circular pupil.

Characteristics of the wavefront sensor:

Mask:	Circular array of holes with a grid distribution
Diameter of the mask:	29.25 mm (size of the image of the primary mirror)
Hole separation:	0.80 mm
Hole diameter:	0.25 mm
Obscuration ratio:	0.5
Number of holes:	750
Focal length of the lens:	-1000 mm (produces a 30 mm defocus)

Measurements

Several series of measurements on the D1.54mT were made in La Silla (described later).
A typical measurement includes:
- different calibration images
- different images of the same star to make averages

Let's treat a measurement from the beginning (the image) to the end (the Zernike coefficients) for the star BS6788 (α=18h18m, δ=-33.8 deg).

The images are recorded in a special format (FITS) used by all the astronomers (here in negative):

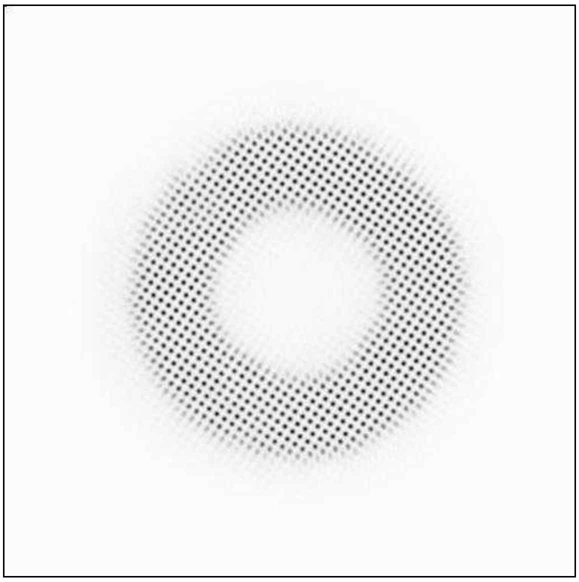
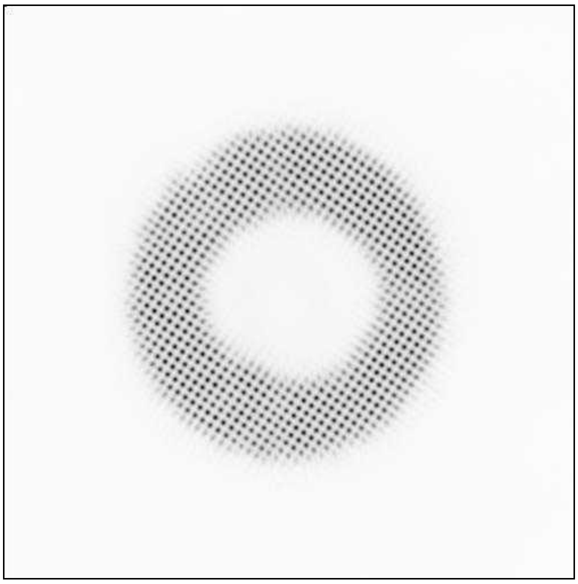



Figure 9: Image from wavefront sensor for the calibration source (left) and a star (right)

Image processing:

At the first step we need to detect the spots and record their positions.
This is done using a program dedicated to the image processing of astronomical data: IRAF (for Image Reduction and Analysis Facility). We use an algorithm that automatically detects the spots by threshold and produces a file with the coordinates of the spots.
The level of the threshold has to be set in the way that we find approximately the correct number of spots. Since we do not only take the primary maxima but also some secondary maxima, we expect about 1000 spots.
Anyway, we noticed that the number of spots is not critical for the process.
The figure below shows possible detected spots corresponding to the two images in Fig 9.

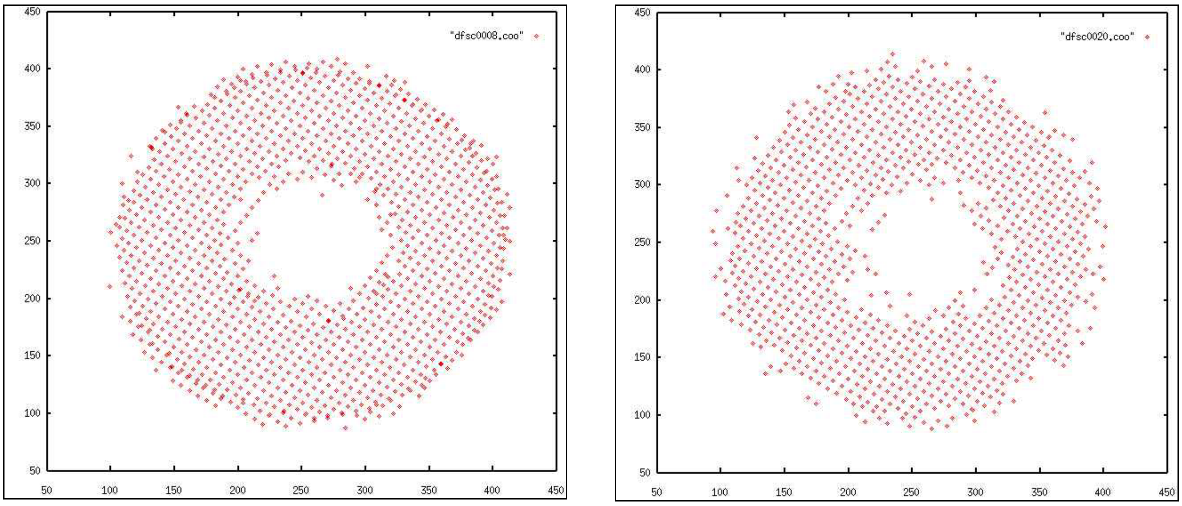


Figure 10: Possible detected spots from the previous images

Calculations of the Zernike coefficients

The last step of the process is to determine the wavefront shape from the spot positions and to calculate the associated Zernike coefficients.
We use a routine under IDL written by Michael Andersen for the active optics system of the Nordic Optical Telescope.
The calibration image must be treated first. Then the program will give directly the correct Zernike coefficients for the measurements images.
The user sets the number of terms for the fitting.

This routine executes the following operations:

1: It arranges the spots along a regular grid.
2: It identifies the primary maxima (spots), based on the definition of the mask.
3: It calculates the deviation between measurement and calibration. This gives the local slope of the wavefront.
4: It fits the slopes in a least square fit with the derivatives of the Zernike "standard" set of polynomials.

Results

Here are the Zernike coefficients calculated for the star BS6788, on axis.
These coefficients are converted from the 21 first polynomials from the "standard" set: the numbering and the normalization are different.
The piston and tilts (terms 1, 2 and 3) don't matter for the image quality.

Zernike Term 4:	-0.222	Focus	
Zernike Term 5:	0.108	Astigmatism	3rd order aberrations
Zernike Term 6:	-0.218	"	
Zernike Term 7:	-0.110	Coma	
Zernike Term 8:	-0.057	"	
Zernike Term 9:	0.071	Spherical	
Zernike Term 10:	-0.152	Trefoil	5th order aberrations
Zernike Term 11:	0.147	"	
Zernike Term 12:	-0.038	Astigmatism	
Zernike Term 13:	0.000	"	
Zernike Term 14:	-0.062	Coma	
Zernike Term 15:	0.034	"	
Zernike Term 16:	-0.092	Spherical	
Zernike Term 17:	0.038	Tetrafoil	7th order aberrations
Zernike Term 18:	-0.016	"	
Zernike Term 19:	0.010	Trefoil	
Zernike Term 20:	-0.014	"	
Zernike Term 26:	0.045	Pentafoil	9th order aberrations
Zernike Term 27:	-0.013	"	

Analysis

To analyze the image quality, it is possible to modelise the system with Zemax. For this we create a pure phase object with the same wavefront characteristics and we focus the light with a paraxial lens with same focal length and F-ratio as the system {telescope + DFOSC}.
We analyze the image on the CCD plane with the assumption that the DFOSC is ideal.
The wavefront errors are:

RMS: 0.16 wave
PV: 1 wave

Here is the Point Spread Function calculated by Fast Fourier Transform.
The peak height compared to the perfect diffraction-limited PSF is 0.33.

The Strehl ratio is 0.32, and with a better focus, it reaches 0.38.

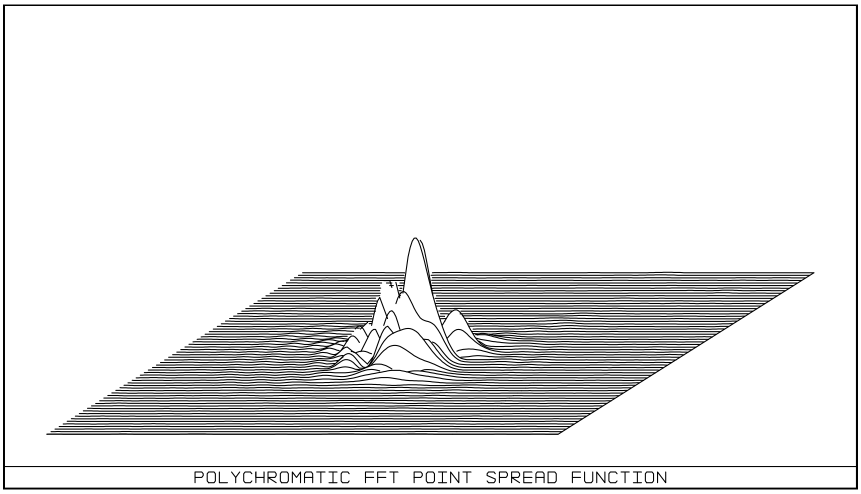


Figure 11: Point Spread Function of the telescope

Here is the Encircled Energy chart, on axis.

80% of the light is inside a circle of radius 9 µm.

There is 73% of the energy in a circle of radius 7.5 µm (pixel size).

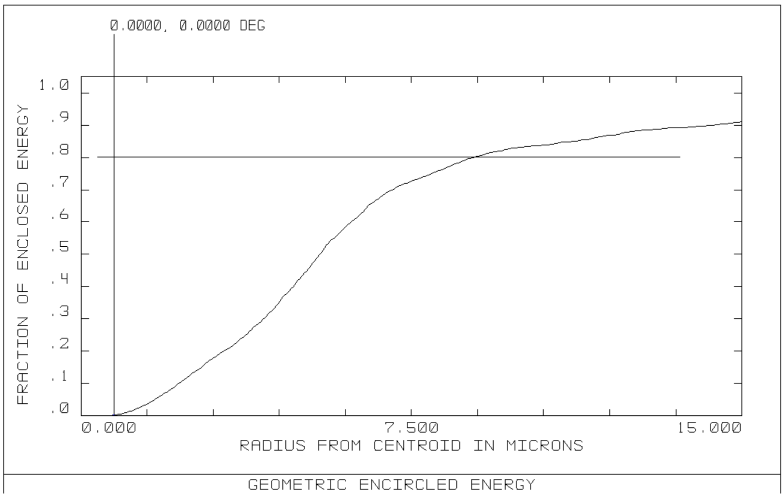


Figure 12: Encircled Energy

Conclusion on the quality of the telescope

Let's assume that this particular measurement, the star BS6788 on axis, at that particular moment, can be representative of the average behaviour of the telescope. In practice, considering that the rest of the instrumentation is perfect, these results would lead to an optical quality (80% encircled energy), on axis, of the order of 9 µm, which is: **0.5 arcsecond** in the sky.

This corresponds to what has been measured with this telescope on the best night in La Silla.

Different series of measurement

Three different series were conducted in order to analyze different issues.

Series	Date	Purpose
Series 1	14/06/2001	Test of the optical quality on one star (5 images)
Series 2	11/08/2001	Long time on the same star (241 images): to observe any possible drift of the aberrations with the time.
Series 3	23/08/2001	Different stars at different telescope positions: to observe any possible correlation between the optical quality and the telescope orientation.

Brief analysis

The optical quality has been correctly analyzed with the first series.

The long time series showed that the results are very faithful and a strong dependence of the first astigmatism term has been reported (see figure below). A further analysis would help to understand this problem.

No clear position dependence was detected from the last series.

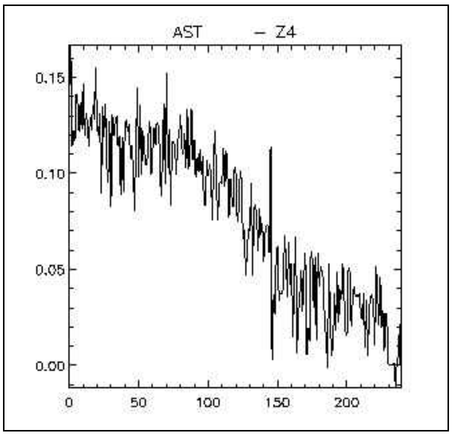


Figure 13: Time dependence of the astigmatism (Z4 versus time in minutes)

III- Optical design for a successor of DFOSC

The purpose of this work is to define a overall layout for a new DFOSC instrument with a better image quality and new functions.
Different issues have to be explored theoretically in order to decide whether the instrument is feasible.
Different options have to be considered and fully discussed.

The ESO opticians Bernard Delabre and Martin Cullum will make the final design.

Objectives:

- Beam spectrally separated in 2 arms, one for UV and blue and the other for the red with the same field size.
- Better transmission in the UV (transmission higher than 90% at 330 nm).
- All other characteristics conserved: focal reduction ratio, size of the parallel beam, pupil position, size of the image, resolution…

Optical constraints:

- The spot radius must be smaller than 7.5 μm for any field position to fit in a pixel of the CCD.
- The pupil aberrations must be small because a grism is placed at the intermediate pupil in the spectroscopic mode.
- No focused ghost images, sky concentration small.

Mechanical constraints:

- We have to consider the space of the mechanical holders in which the lenses have to be mounted.

Others constraints:

- Price
- Manufacturing complexity
- Alignment easiness

…

Considering the new objectives, the following issues have to be studied:

- How to separate the beam most efficiently?
- How to make a good UV system?
- How to calculate the sky concentration (sum of the different ghosts images)?

For all of these studies, we have used the optical design program ZEMAX®.

The different systems were modeled after the D1.54mT or after a perfect lens with the same focal length and F/ratio.

The systems DFOSC and DFOSC2 (designed by Bernard Delabre in 1997) have been taken as examples or starting points for new designs.

Practical work with the optical design program

In our case, we have the advantage that a previous design already exists and there are no reasons to change the model.

Therefore we can skip the preliminary phase where one has to decide the type of system: refractor or reflector, the numbers of surface…

Starting from the old design, we just have to take into account the new parameters and re-optimize the design.
The success of the work is then mostly related to the understanding of the optimization process.

The optimization process

The optical design program ZEMAX® has a very powerful optimization tool.

Like the other design program, the optimization try to minimize the **merit function** by small changes on the **variables.**

There are three different optimization programs:
- the normal program for simple changes
- the Global search that searches in wider limits to define a good starting point
- the Hammer optimization that searches the best final design

The variables here are all the curvatures and thickness.
The last two programs are even capable to switch the glasses within a selection.

The difficulty is to find a good starting point for the optimization and to orient it toward what we want with a relevant merit function.

The merit function

The merit function is a function whose value represents how close the system is from the ideal design. The merit function can be described simply as:

$$\Phi = \sum_i w_i^2 \; O_i^2$$

where O_i is an operand and w_i the corresponding weight.

The goal is to define the relevant operands and to play with the different weights.

In this problem, the appropriate operands are:
- minimal wavefront error for the image quality (in the default merit function)
- geometrical constraints for each lens (no negative length)
- geometrical constraints for the system (maximum length)

To direct more specifically the optimization, other operands can be used to face different problems:
- no particular aberrations (defined by the Zernike polynomial or a specific operand)
- position of the pupil

…

Beam separation study

One important specification for the new DFOSC design, is the separation of the beam in two: one way for the UV and blue, up to 550 nm, and the other way for the rest of the spectrum.
The separation has to be as early as possible in the system so that, after the separation, each way can be optimized for its wavelength domain: best color correction, best glasses transmissions, best coatings… Ideally, the entire system is divided in two.

But the beamsplitter may produce aberrations that could be difficult to get rid of. We also have to consider the place occupied by the beamsplitter.
So, we have made different theoretical studies to explore the different possibilities for splitting the beam: different beamsplitters and different configurations.
There are two possible components for splitting the beam:

- a plane parallel plate
- a cube

Moreover, the beam can be splitted in different places in the system: before the collimator and after it.
We have studied both components in order to determine which one was the most appropriate.

A dichroic plate as a beamsplitter

This component was the first we thought about. So we made many efforts to succeed making a design with it.
A beamsplitter plate is at least 5 mm thick with coatings on the first side and tilted by 45° around **X**. This kind of component introduces a decenter in the **Y** direction in the transmitted light section and for every configuration. The diagram below illustrates it for a parallel beam.

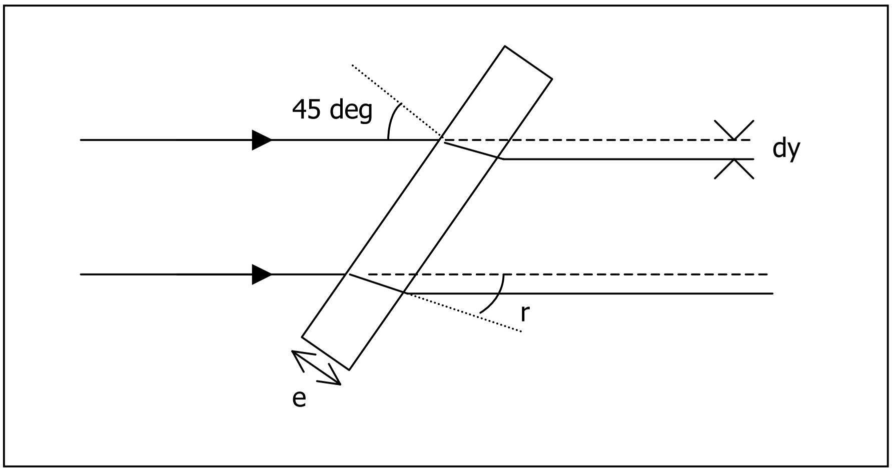


Figure 14: Decenter introduced by a plate beamsplitter

The decenter can be calculated using the following equation: (the variables are showed on the diagram)

$$dy = e\frac{\sin(45° - r)}{\cos(r)}$$

ex: for 5 mm of BK7 : dy=1.67 mm

This decenter will have to be considered in the theoretical studies and in the mechanical mounting of the system.

The separation after the collimator

This is the simplest case. The separation takes place in the parallel beam section. Therefore the beamsplitter introduces no aberrations at all (this is also true for the cube). But the advantage of optimizing the elements of the collimator for each wavelength domain is lost.

This option is interesting because it is absolutely sure that such a design is possible. But we would prefer to separate the beam earlier in the design.

The separation before the collimator

In this option, the beam is splitted just after the telescope focal plane. The whole collimator is therefore entirely dedicated to both wavelength domains.
But the beam is not parallel in this section: it is diverging.

When one adds a plane parallel plate tilted by 45º in a diverging beam, it introduces aberrations. These aberrations are mainly **astigmatism** and **lateral color**, but also spherical aberration and coma. When the pupil is placed at the infinity, which is approximately the case, these aberrations are constant with the field.

Let's have a look at the aberrations introduced by the beamsplitter on axis: (a BK7 plate tilted by 45° in the telescope beam)

Plate thickness	5 mm	10 mm
Astigmatism	**1.3 mm**	**2.6 mm**
Lateral color	**12.6 μm**	**25.2 μm**

It is impossible to correct these aberrations with spherically symmetrical components.
For astigmatism, we need a cylindrical lens (or another plate tilted around the other direction), and for the lateral color, we need a wedge.

Problems with the use a wedge for the corrector

The use of a wedge creates a lot of different problems in the system.

We made a study with a beamsplitter (a 5 mm BK7 plate) and a corrector (5 mm toroidal+wedge plate of angle θ).

The wedge introduces a tilt of the optical axis (α) around **X** according to:

$$\alpha = \text{arcsine}\ (n \sin \theta) - \theta$$

But the most annoying effect is probably that the wedge introduces a tilt of the image plane (β). That means that one has to tilt the image plane around the **X** direction to have the best image quality.

The figure below gives a summary of the different tilts (angles are greatly exaggerated). The image plane (in blue) is tilted.

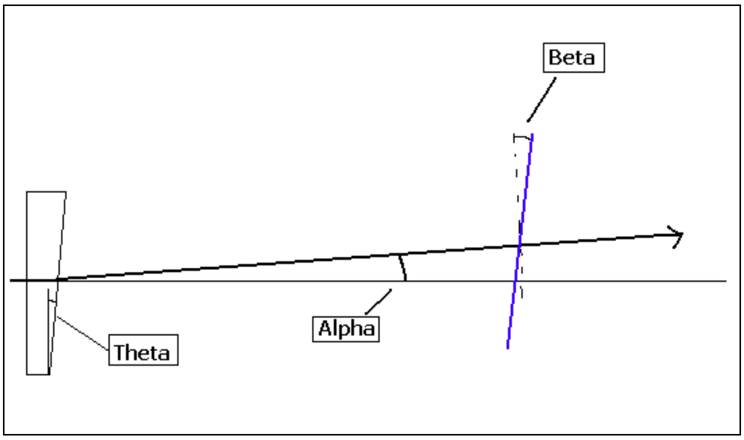


Figure 15: Tilts introduced by the corrector

Let's compare the image quality with and without tilting the image plane. The figure below shows the spot diagrams with and without tilting the image plane (The two upper boxes are the positive and negative maximum field positions in **Y** direction).

Spot diagram with tilt of the image plane:

Spot diagram without tilt of the image plane:

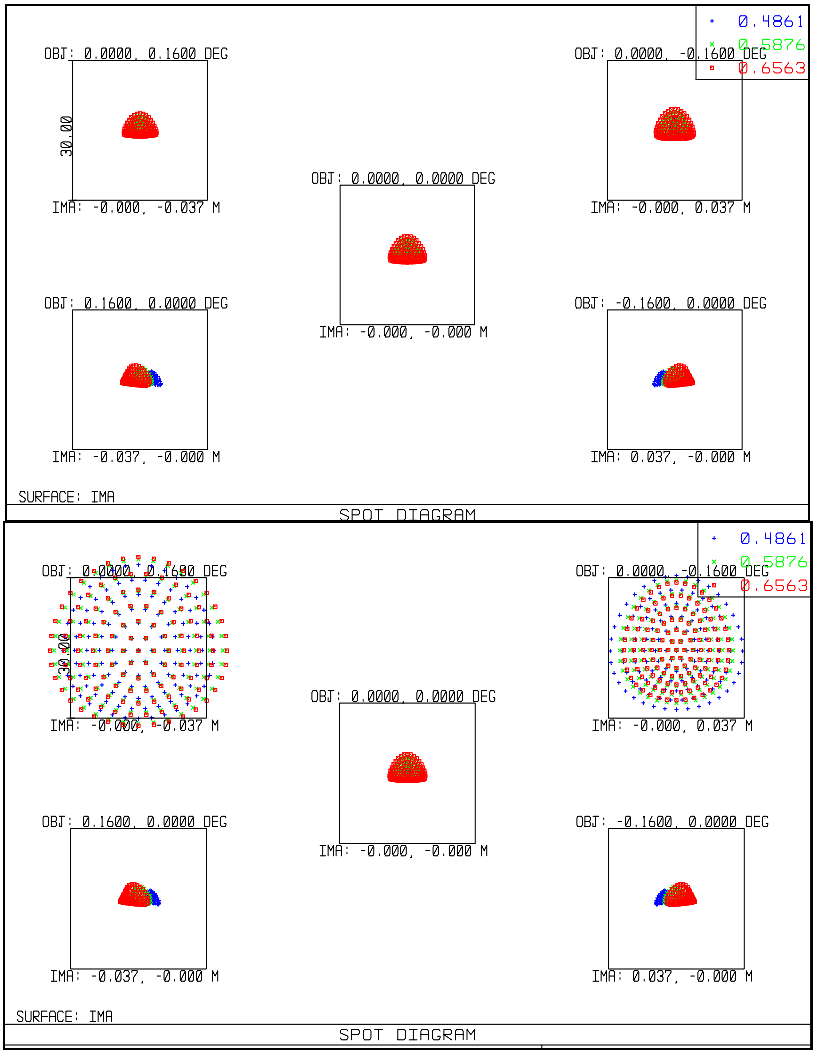


Figure 16: Comparison of the spot diagrams with and without tilting the image plane

In this particular case, we have the following values for the different angles:

dy = 1.67 mm
$\theta = 0.5°$
$\alpha = 0.25°$
$\beta = 0.4°$

These tilts make the mechanical structure much more complex to realize.
They also make the focusing of the CCD more complicated (two directions to control: focus and tilt) and will probably cause alignment problems in real systems.

To conclude, we showed that the use of a dichroic plate complicates the system tremendously.
It would be wise to avoid it and to find another method to separate the beam.

New Idea: The separation in a roughly parallel beam

One alternative of the former problem is to place the plate in the middle of the collimator.
The principle is to create a **roughly** parallel beam as simply as possible and early as possible with a **pre-collimator**. Ideally, the pre-collimator is only a doublet or a triplet.
The beam will be separated in the pre-collimated space and the collimator is ended with an afocal system that makes the proper parallel beam. The idea is that if the beam is almost parallel, the plate won't introduce too many aberrations, and they can be corrected in the afocal system.
Only the pre-collimator needs to be optimized for the whole wavelength domain.

The principle is resumed in the diagram below.

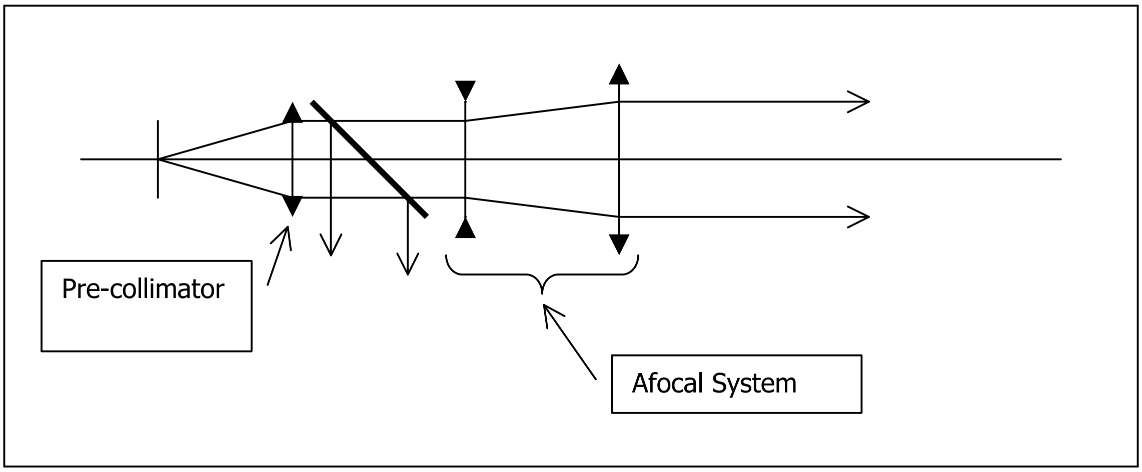


Figure 17: Principle of the pre-collimator

We noticed that the insertion of the plate in the precollimated section has not any noticeable effect on the image quality once the beam is reasonably parallel.
Then the afocal system seems to be fairly easy to design to obtain a good parallel beam.

This solution might be a good compromise between the positions after and before the collimator.

Using a cube beamsplitter

A cube beamsplitters consists of matched pairs of right angle prism cemented together. The hypotenuse of one prism has a dichroic coating.

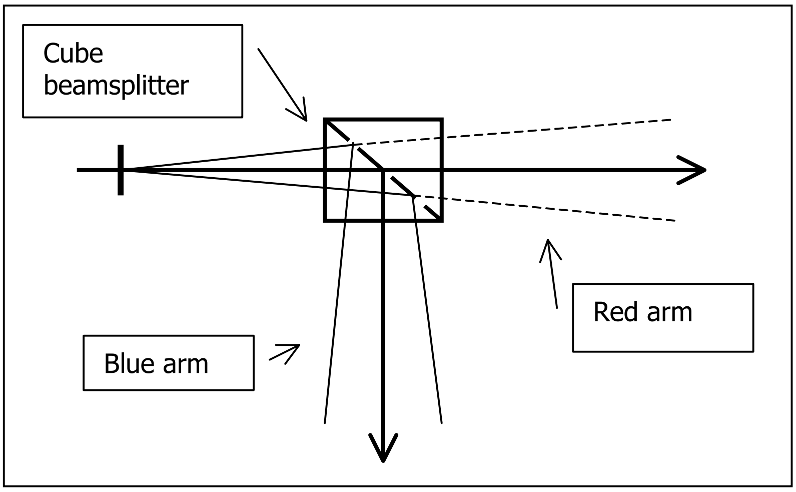


Figure 18: Optical layout of a cube beamsplitter

The advantage is that, in both arms, it acts exactly like a thick plane parallel plate, even in diverging beam. So it introduces much less aberrations than a beamsplitter plate. Moreover, there is no tilt or decenter of the optical axis neither any tilt of the image plane.
The ghost reflections between the two faces of the cube are less disturbing too.

The aberrations introduced by a cube are:

- Lateral color: 1.5 μm
- Axial color: 500 μm
- Small spherical aberration
- No astigmatism
- No coma

All of these aberrations can be corrected in the rest of the instrument.

However, the optical quality of the cube must be perfect: excellent precision of angles between the surfaces and less than $\lambda/4$ surface error on each side. For a piece of this size, it requires a great precision in the manufacturing.

This component is the ideal one for our purpose tough it will be rather expensive.

UV arm design

The UV arm of the instrument needs to have a good transmission between 330 nm and 550 nm. The problem is that the typical glasses used in optical design have unfortunately very bad transmission in this domain.
The purpose of this study was to investigate the different possibilities to build an UV arm. The goal is to have at least 90% at 330 nm.

The main problem is the lack of glass available for this wavelength range. The decreasing of the number glass types due to environmental concerns doesn't arrange the situation. In the Schott catalogue, there are only 3 good in UV and easily available glasses.

Here are the transmittances of them. BK7 has been added for comparison.

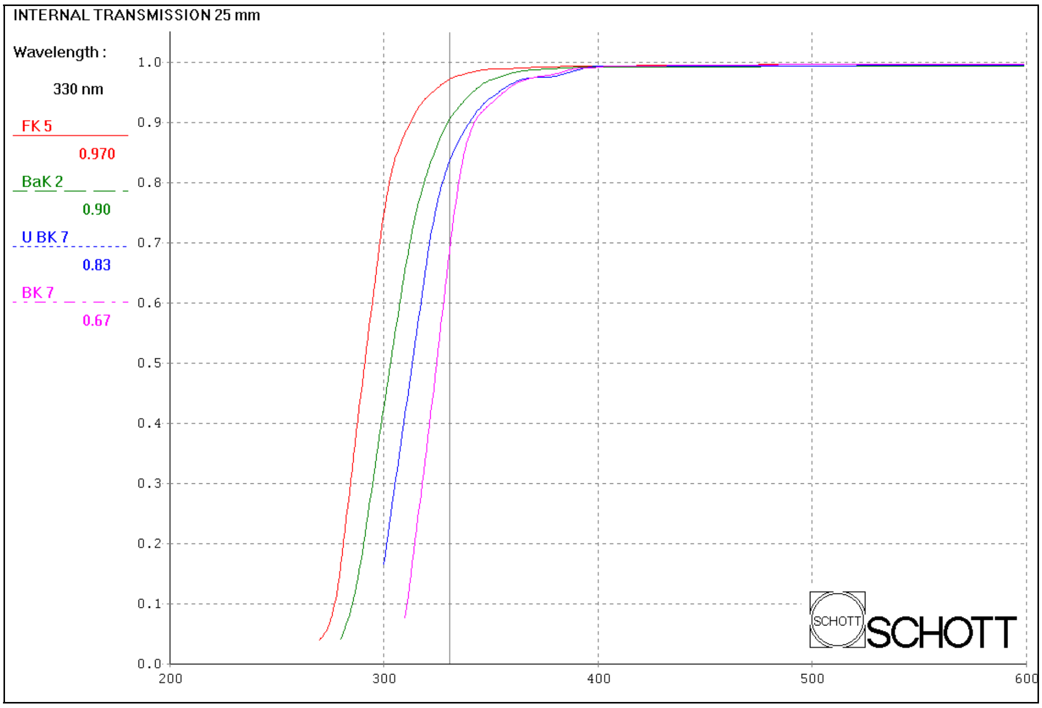


Figure 19: Possible UV glasses from Schott

To solve this problem, the designers use special glasses: CaF_2 and fused Silica.
These glasses have perfect transmission down to 300 nm.
Let's summarize the properties of these different glasses:

Glass (25 mm)	Transmission at 334 nm	Index Nd	Abbe vd	Coefficcient of expansion (10^{-6} K)
BK7	0.77	1.516800	64.17	7.1
U BK7	0.86	1.516800	64.29	7
BaK2	0.92	1.539960	59.71	8
FK5	0.976	1.487490	70.41	9.2
fused Silica	> 0.99	1.458464	67.821	~ 0
CaF2	> 0.99	1.433849	94.996	18.9

We can notice that all these glasses have low dispersion and one has very low dispersion. If we want to achromatize the instrument we need to use glasses with dispersion values as different as possible.

CaF_2 and Silica could form a good couple, but, Silica has a quasi-null coefficient of thermal expansion and CaF_2 has a very high one. So it is impossible to cement them (for the diameter of the lenses we consider).
So, one ends up with an instrument with a lot of air/glass surfaces which makes it expensive, hard to align and requires very good coatings. An instrument of this kind is so sensitive to temperature that it requires a full thermal analysis.

Let's take the UVES instrument as an example. UVES is also a dual beam instrument installed on one of the VLT telescopes.

The blue (top) and red cameras are showed on the figure to the right.
The blue camera is a succession of CaF_2/Silica lenses not cemented. Two air spaces vary with the temperature to compensate the thermal expansion.
In comparison, the red camera is much more simple and easier to align.

So, this solution is working but demands a lot of efforts and money.

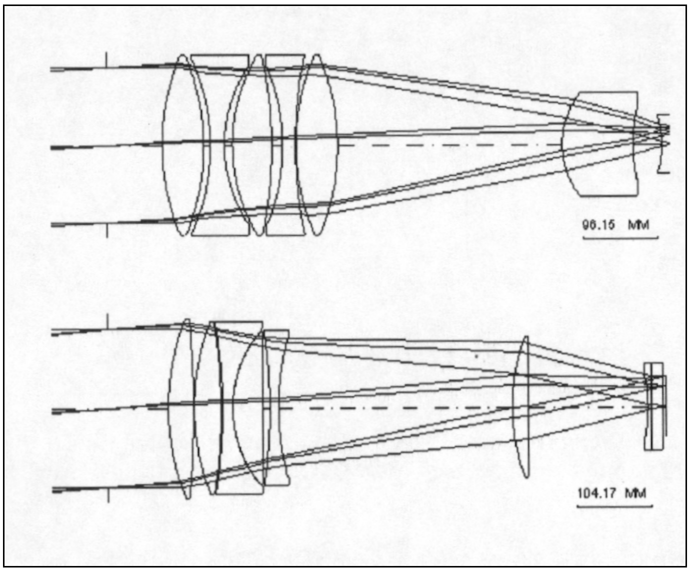


Figure 20: Comparison between blue and red cameras of UVES

We can think about other possibilities for helping designing UV instruments.

- Tough it is impossible to cement CaF_2 with Silica, it is possible to make cemented doublets or triplets with CaF_2 and normal glasses (see list above).
- Aspherisations would reduce the number of surfaces and then make the instrument simpler.
- The use of optical liquids is very promising in such problems because it gets rid of the cementing restriction. However, new issues have to be considered.

We have found that, in the designing of UV instruments, very few solutions are possible.

But, from experience of other instruments, we know that making a good UV system is possible (UVES for example). Since Bernard Delabre is one of the designers of UVES, he will probably adopt this solution.

Considering that the DFOSC project has not a so big financing, it will be interesting to make further practical analysis of this problem.
We think that the adoption of one or a couple of the last proposed solutions makes the achievement of a good UV arm quite likely.

Ghost Analysis

Focused Ghost

A ghost image is an image created by two reflections (or more) inside the optical system: a ray is reflected on a lens or the CCD, comes back and is reflected again.
There is a possibility that these reflections are focused on the same image plane.

In the example given Fig 21, a very focused ghost was reported on the image plane.
An image of a star in such a system will have a symmetrical ghost image, which is not acceptable. This configuration was of course immediately rejected.

So, it is important to analyze every possible ghost in the system. There are very few tricks to guess whether a system will have annoying ghosts or not. The analysis has to be done afterwards to validate the system.

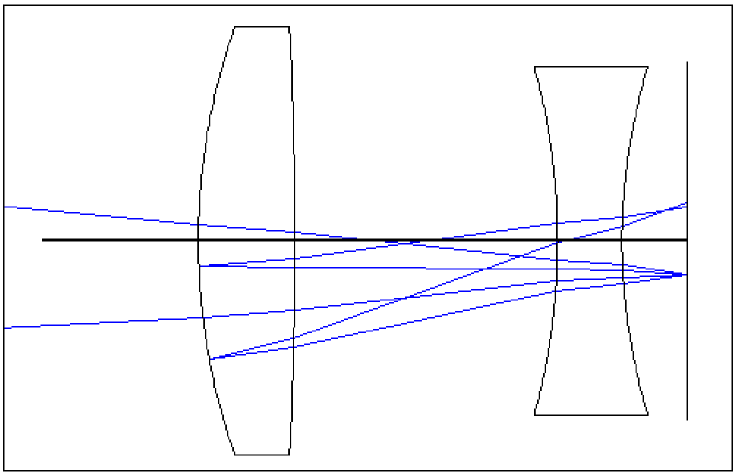


Figure 21: Example of a focused ghost image

It is quite a long job for a big system because one has to consider every combination in the system (except the ghost due to a reflection on a cemented surface because the reflection percentage is extremely small).
Typically, for a system with n surfaces, there are $(n^2-n)/2$ possible ghosts. Fortunately, the modern optical design programs have powerful tools to carry out ghost analysis. Zemax® for example can generate the optical files of any ghost in the system.

Sky Concentration

Another aspect of the ghosts is the so-called "sky concentration".

If we take into account all the light coming back on the detector after the different ghosts' reflections, we can notice that the detector is not uniformly illuminated.
The contribution of each ghost will concentrate the light coming from the whole image (principally the sky background) non-uniformly. If we make the sum of all the ghosts, we can see that the light is concentrated in a central region.
The simplest test for the observation of the phenomenon is to make a flat field image (i.e. with a perfectly uniform object) and look at the result on the CCD.
Sky concentration is mostly annoying when photometric measurements have to be made.

The amplitude of both ghost effects is of course dependent on the quality of the coatings on the lenses' surface.

Practical Ghost Analysis

Typically, for one particular system, two parameters have to be studied:

- On each ghost: radius of the ghost image of an object in the center of the field. This parameter indicates if the ghost is focused or not.
- On the complete system: the sky concentration.

We realized several macro commands with the programming language of ZEMAX (see annexe D). The programs perform a real ray analysis with the ghosts files generated by ZEMAX. That means that we send a high number of rays covering all the field and pupil positions and see where they hit the detector.

A first program (ghost.zpl) automatically calculates the "radius" parameters for every relevant ghost and lists them. Then one has to go trough this list and decide which ghosts could be dangerous.

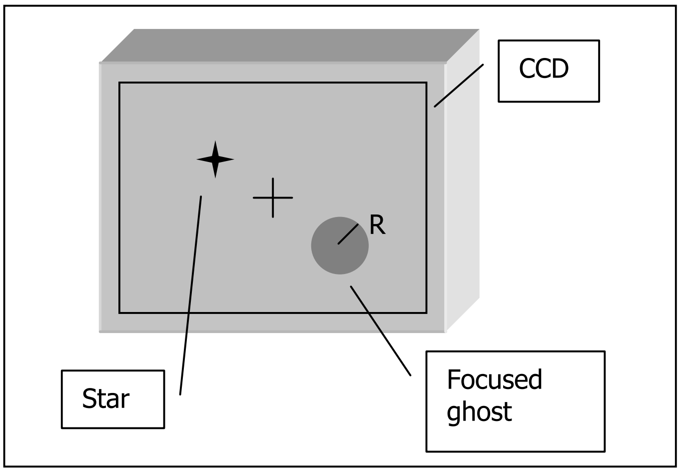


Figure 22: Example of a focused ghost

Let's take an example. The size of the image of a star (equal to the PSF of the instrument) is typically matched to the pixel size of the CCD, say 15 μm.
If the reflection coefficient is 0.01 on each surface, we have 0.01x0.01=0.01% of the intensity of the star (Is) re-imaged on the ghost.
That intensity is concentrated in a disk of radius R, so the mean intensity of one pixel of the ghost (Ig) is:

$$Ig \sim Is / R^2$$

If the radius of the ghost is 150 μm, the surfacic intensity is divided by 10,000 again.

Therefore, we think that we have to consider as potentially annoying only the ghosts whose radius is of the order of the pixel size.
The radius of the ghost taken as an example on the previous page was only 27 μm on axis!

A second program (skyglob.zpl) calculates the sky concentration of a complete instrument.
It takes every relevant ghost, send a high number (101x101) of rays covering all field and pupil position in one dimension and measure the intensity distribution on the CCD with a sampling of 40. Then it sums this distribution for all the ghosts to obtain a distribution of the sky concentration.

This program gives a good indication of the level of sky concentration, but not an exact value.

Here is the sky concentration calculated for DFOSC:

Max value: 7064
Min value: 2430

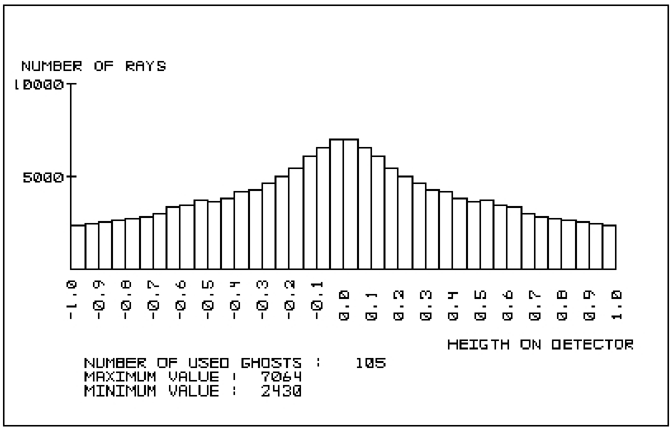


Figure 23: Sky concentration distribution for DFOSC

Normalization

This number of rays has to be normalized with the corresponding background on the detector.

First we should divide the number of rays by the square of the reflection coefficient (r).
Let's take: $1000 < r^2 < 10\,000$
(depending on the quality of the coatings, of the reflectivity of the CCD,…)

An average value of background on the CCD would be equal to the total number of rays divided by the sampling: backgroud: ~ 10 000 / 40 = 250

Therefore, in DFOSC, the sky concentration creates a difference of 5 counts on 250 that is 0.5%.

The program was also tested with instruments were the sky concentration is high. The comparison was relevant.
Fortunately, in most of the instruments, the sky concentration is neglectible.

Conclusion

During this training period, a lot of different problems have been studied.

The wavefront sensing appears to be very precise and helpful for the understanding of the behaviour of the telescope.
After the beam separation study conclusions, it is very likely now, that the beam splitter will be a cube in the future design.
The UV study proved that this topic is very critical, but some solutions still give hopes to success.
Some theoretical subjects, for example ghost analysis, have lead to the achievement of new tools in the domain.

It was also extremely interesting to see the optical design as an integral process, involving different other aspects like electronics, mechanics, software creation.

Moreover, working in an astronomical environment was very exciting to me and I learnt a lot on this domain.

I hope that this work will contribute to a good improvement of the Danish 1.54 m Telescope.

Annexes

A: References

B: List of figures

C: Layout of DFOSC2

D: Example of a ZEMAX macro-command

Annexe A: References

Books:

- Smith: **Modern Optical Engineering**, 2000, SPIE press McGraw Hill
- Fischer, Tadic-Galeb: **Optical System design**, 2000, SPIE press McGraw Hill
- Laikin: **Lens design**, 1995, Dekker
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- Fleury, Mathieu: **Images Optiques**, 1968, Eyrolles
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- Jenkins, White: **Fundamentals of optics**, 1976, McGraw Hill
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- **Handbook of optics**, vol. I-IV, 1995, McGraw-Hill
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Articles:

- T. Korhonen : **Interferometric method for optical testing and wavefront error sensing**, 1984, Proc. SPIE vol. 444
- T. Korhonen et al. : **Hartmann interferometric testing of large mirrors**, 1991, Proc. SPIE vol. 1531
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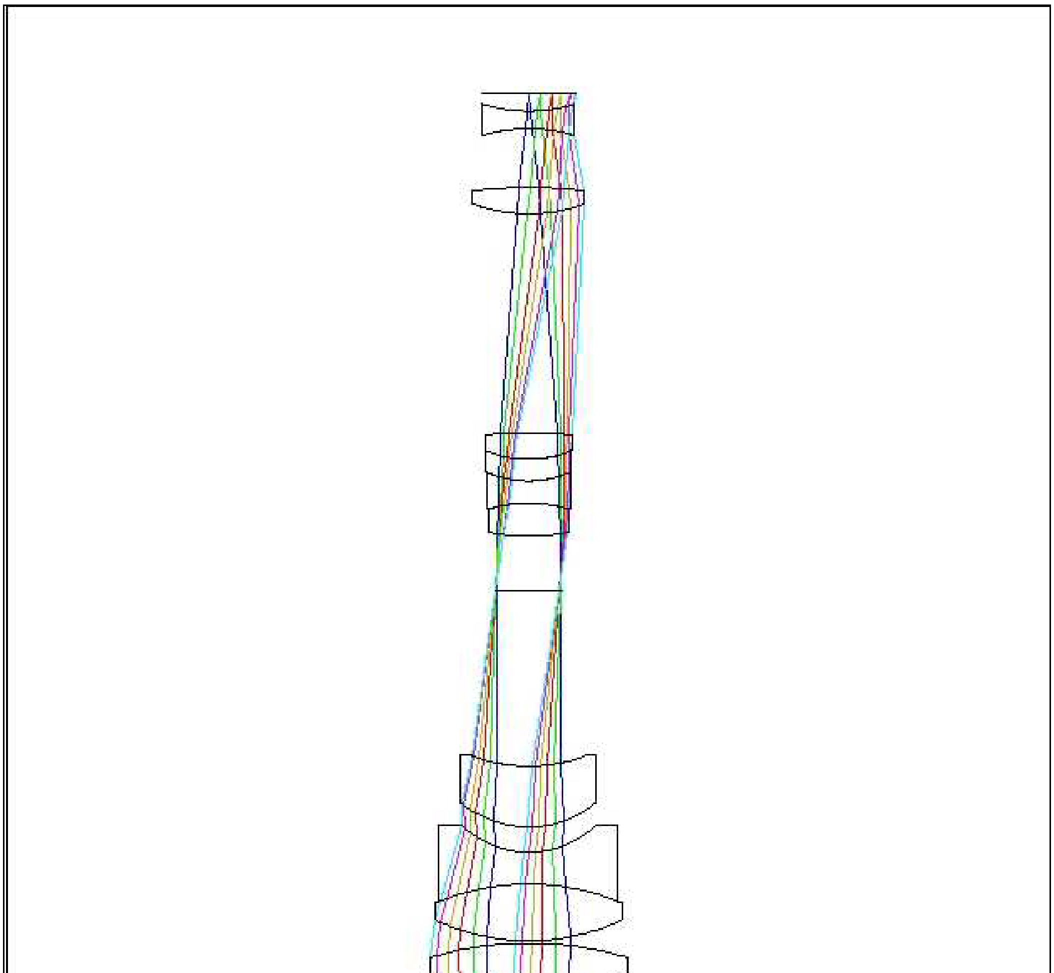
- S. D'Odorico et al. : **The performance of UVES and highlights of the first observations of stars and quasars**, 2000, Proc. SPIE vol. 4005
- H. Dekker et al. : **Design, construction and performance of UVES**, 2000, Proc. SPIE vol. 4008
- J.G. Robertson et al. : **ATLAS : a Cassegrain spectrograph based on volume phase holographic gratings**, 2000, Proc. SPIE vol. 4008

Others:

- Delabre: **DFOSC2 optical design,** 1997, Internal ESO report
- Delabre: **Focal Reducer for the Danish 1.5m telescope,** 1991, Internal ESO report
- Michael Andersen: **DFOSC: A multi-purpose instrument for the Danish 1.5m telescope,** 1992, Master's Thesis, Copenhagen University Observatory
- Zemax 9.0 User's Guide, 2000
- Several SupOptique courses

Annexe B: List of figures

Annexe C: Layout of DFOSC2



Annexe D: Example of a ZEMAX macro-command

```
! skyglob.zpl
!
! Written by Bruno Hiberty 08/2001
!
! For the ghost analysis of DFOSC-like systems
!
! Calculates the sky concentration for the whole system
!
! Sends 10 201 rays for each relevant ghost and calculates the positions of each ray on the detector
!
! The merit function window should be closed. (Ideally, every window should be closed)
!
! Be careful to have the right parameters:
! first glass surface:
fgsurf=5
! image surface:
lastsurf=26
! pupil surface:
pup=16
!path:
path$="C:\ZEMAX designs\"
!primary wavelength
primwav=1
!size detector
sizedet=21.7
!resolution : multiple of two (<=100)
res=40
!unit 1: mm      1000 : m
uni=1
!system
sys$="Tfosc"
!
!Program starts
!
title$="Sky Concentration of "+sys$
PRINT title$
PRINT
nsurf=NSUR()
SETVECSIZE(100000)
numsys=0
FOR l=1,res,1
        VEC2(l)=0
NEXT
FOR i = fgsurf+1,lastsurf,1
        FOR j = i-1,fgsurf,-1
!
!               open the correspondent file
!
!the pupil surface should not be considered
!
                if ((i==pup)|(j==pup)) then goto 1
                IF (i>9)
                        FORMAT 2.0
                        i$="0"+i
                ELSE
                        format 1.0
                        i$="00"+i
                ENDIF
                IF (j>9)
                        FORMAT 2.0
                        j$="0"+j
                ELSE
                        format 1.0
                        j$="00"+j
                ENDIF

        file$=path$+"Gh"+i$+j$+".zmx"
                LOADLENS file$
                nsurf=NSUR()
!
!checks if there is a cemented surface
!
                glassi$=$GLASS(i+2*(i-j)+2)
                glassj$=$GLASS(j-1)
                glassimin$=$GLASS(i-1)
                glassjplus$=$GLASS(j)
                leni=slen(glassi$)
                lenj=slen(glassj$)
                lenimin=slen(glassimin$)
                lenjplus=slen(glassjplus$)

        icement=((lenimin>0)&(leni>0))

        jcement=((lenjplus>0)&(lenj>0))
                IF (icement|jcement)
                        GOTO 1
                ENDIF
!
!calculates the sky concentration for this ghost
!Put every heigth values in VEC1
!
                k=0
                FOR m=-100,100,2
                        FOR n=-100,100,2
                                RAYTRACE 0,m/100,0,n/100,primwav

        heigth=RAGY(nsurf)*uni

        rayerror=RAYE()
```

```
                    IF
((heigth!=0)&(rayerror==0))&((heigth>-
sizedet)&(heigth<sizedet))

    vignsurf=RAYV()
                         IF
(vignsurf!=1)

    k=k+1

    VEC1(k)=heigth

    ENDIF
                    ENDIF
               NEXT
          NEXT
          IF (k==0) THEN GOTO 1
!
!         Samples the values in the final
array
!
          FOR l=1,k,1

    chan=VEC1(l)/sizedet+1

    channel=INTE(chan*res/2)+1

    VEC2(channel)=VEC2(channel)+1
          NEXT
          numsys=numsys+1
          LABEL 1
    NEXT
NEXT
!
! Display the results
!
GRAPHICS
max=0
min=10000000
FOR l=1,res,1
    IF (VEC2(l)>max) THEN
max=VEC2(l)
    IF (VEC2(l)<min) THEN min=VEC2(l)
NEXT
maxunit=POWR(10,INTE(LOGT(max))+1)
IF (max/maxunit<0.5) THEN
maxunit=maxunit/2
IF (max/maxunit<0.5) THEN
maxunit=maxunit/2
FORMAT 5.0
gtext 200,1000,0,maxunit
line 800,3000,500+300*21,3000
line 800,3000,800,1000
line 750,1000,850,1000
line 750,2000,850,2000
gtext 200,2000,0,maxunit/2
gtext 300,800,0,"Number of rays"
FORMAT 8.0
FOR l=1,res,1
    PRINT VEC2(l)
    line 800+6000*(l-
1)/res,3000,800+6000*(l-1)/res,3000-
VEC2(l)*2000/maxunit
    line
800+6000*l/res,3000,800+6000*l/res,3000-
VEC2(l)*2000/maxunit
    line 800+6000*(l-1)/res,3000-
VEC2(l)*2000/maxunit,800+6000*l/res,3000
-VEC2(l)*2000/maxunit
    NEXT
FORMAT 2.1
FOR l=1,21,1
    gtext 500+6000*l/20,3500,90,(l-
11)/10
NEXT
gtext 5000,3800,0,"heigth on detector"
FORMAT 5.0
resnum$="Number of used ghosts :
"+numsys
max$="maximum value : "+max
min$="minimum value : "+min
samp$="Sampling resolution = "+res
PRINT resnum$
PRINT max$
PRINT min$
PRINT samp$
gtitle title$
gdate
gtext 1000,4000,0,resnum$
gtext 1000,4150,0,max$
gtext 1000,4300,0,min$
gtext 1000,4500,0,samp$
PRINT "End of analysis"
END
```