Analysis of the Sequence Of Phase Correction in Multiconjugate Adaptive Optics

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The EST

The European Solar Telescope (EST) is a 4-meter diameter world-class facility designed to measure the properties of the solar magnetic field with great accuracy and high spatial resolution. It will be located in the Canary Islands,Tenerife.

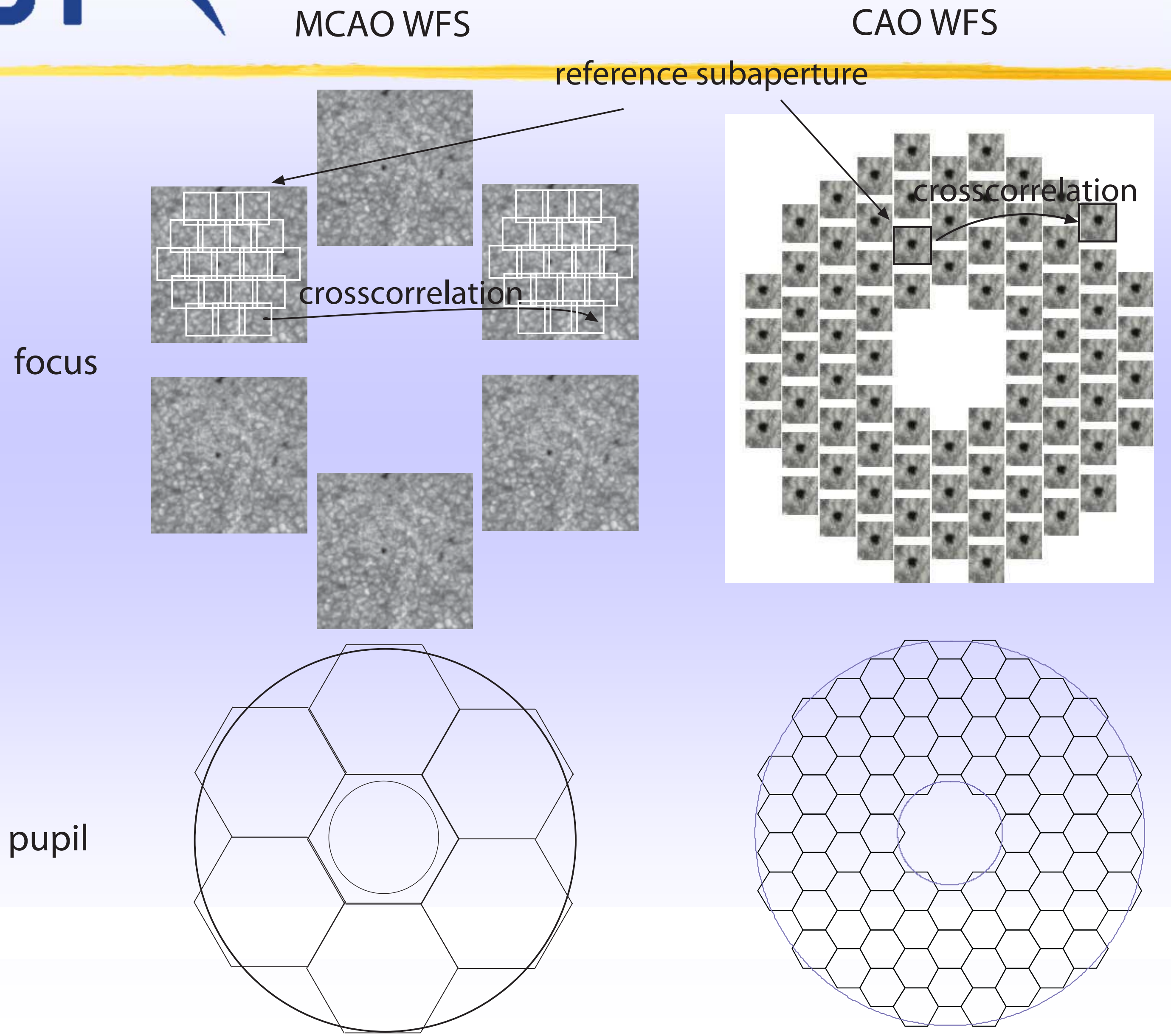
Adaptive Optics (AO) at the EST

The optical layout of the EST features two main AO modes:

- **A conventional AO (CAO):** The CAO mode uses the ground layer Deformable Mirror (DM) and a high order correlating Shack-Hartmann wavefront sensor (HOWFS).
- **A Multi-conjugate AO mode (MCAO):** The MCAO mode uses five DMs conjugate at different heights. It uses the high order sensor for the pupil DM and one wide field low order sensor (LOWFS), with less sub-apertures but wide FoV, that senses the field-dependent and weaker aberrations of the high altitude turbulence.

Parameter	AO	MCAO
DM heights [km]	0	0, 1.6, 6.6, 10, 23
Spatial sampling [cm]	8	8, 30, 30, 30, 30
Sensing field points	1	19
Subaps/pupil diameter	50	13

MCAO systems at the EST



Solar MCAO

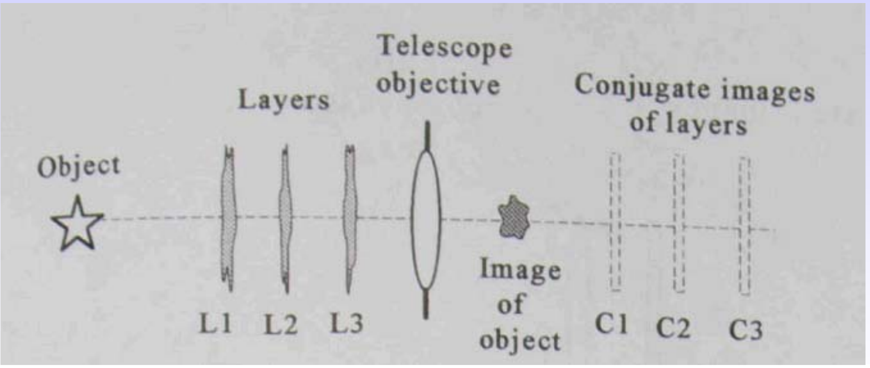
- *Most solar observations are performed at visible wavelength*
- *Solar wavefront sensor uses extended objects*
- *Wavefront pupils are large and suffer from intrinsic anisoplanatism*
- *Solar observations are performed at very high airmass thus turbulent volume increases with angular distances ~ sec (α)*
- *The sky coverage is 100%*

Order of the DMs

There are two options to place the DMs in the optical train:

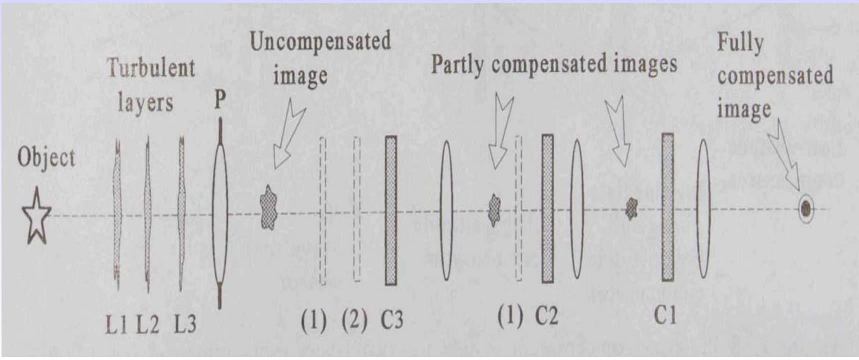
Correcting the layers in the same order as they are optically conjugated:

this is the way the correction is usually performed in all night-time infrared MCAO systems.



Reimagining, correcting the layers in the order inverse to conjugation:

this is the way the correction is performed in the solar MCAO systems being designed.



From "Adaptive Optics for Astronomical telescopes", J.W.Hardy, Oxford University Press 1998

Order of the DMs

- There are practical implications that degrade the performance and have prevented any solar MCAO system to close the loop at high order.

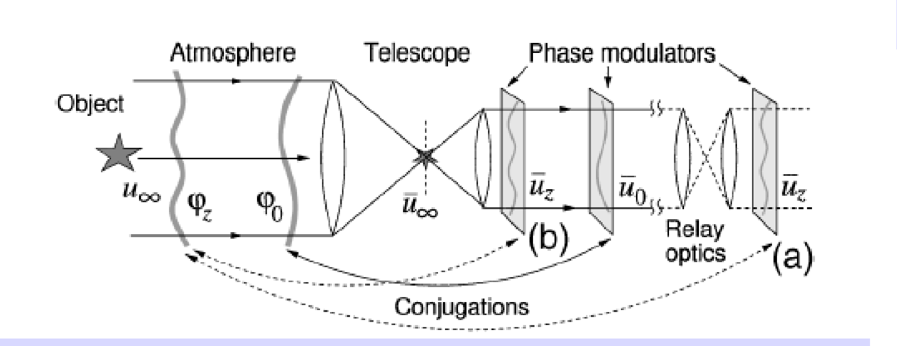
- According to Schmidt *et al*. *it is due to dynamic pupil distortion caused by high-altitude DMs yielding a misregistration between DM0 and the small subapertures on-axis WFS.*

- The solution so far has been placing the HOWFS before the high altitude DMs, and filtering the low order modes. The HOWFS is only used to control the high order modes of the pupil DM, that cannot be seen by the LOWFS.

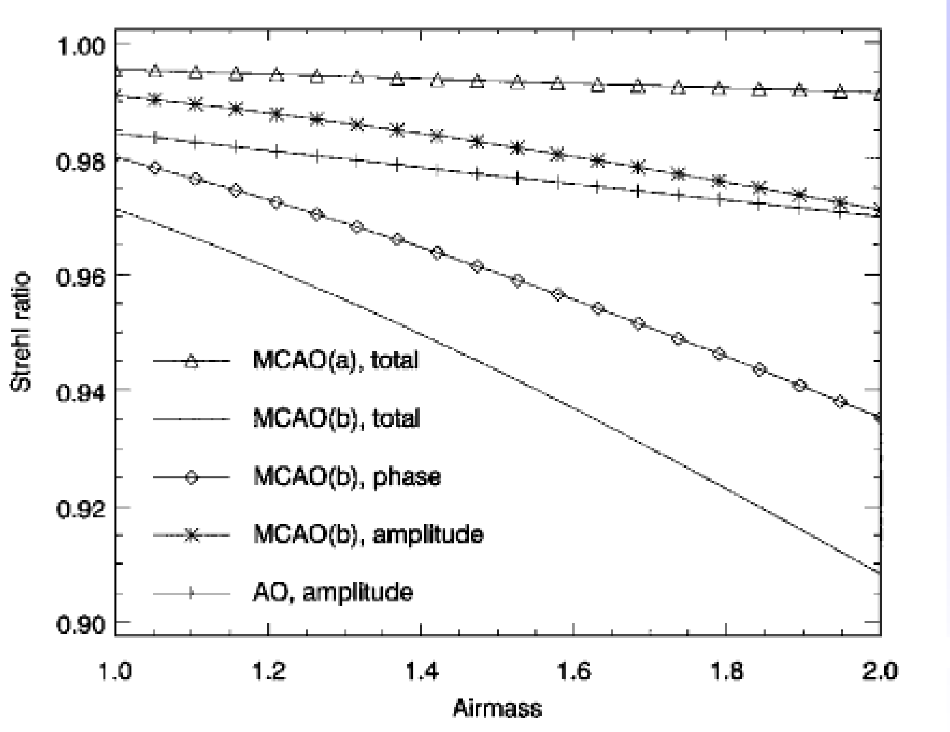
- An alternative solution could be to correct turbulence layers in the order that are optically conjugated . **Does it improve the performance of the system?**

Scintillation effects on wavefront propagation

It has been shown by Montecarlo simulations that a perfect cancellation of amplitude and phase is only achieved if the correction is applied sequentially in reverse order of turbulence occurrence.

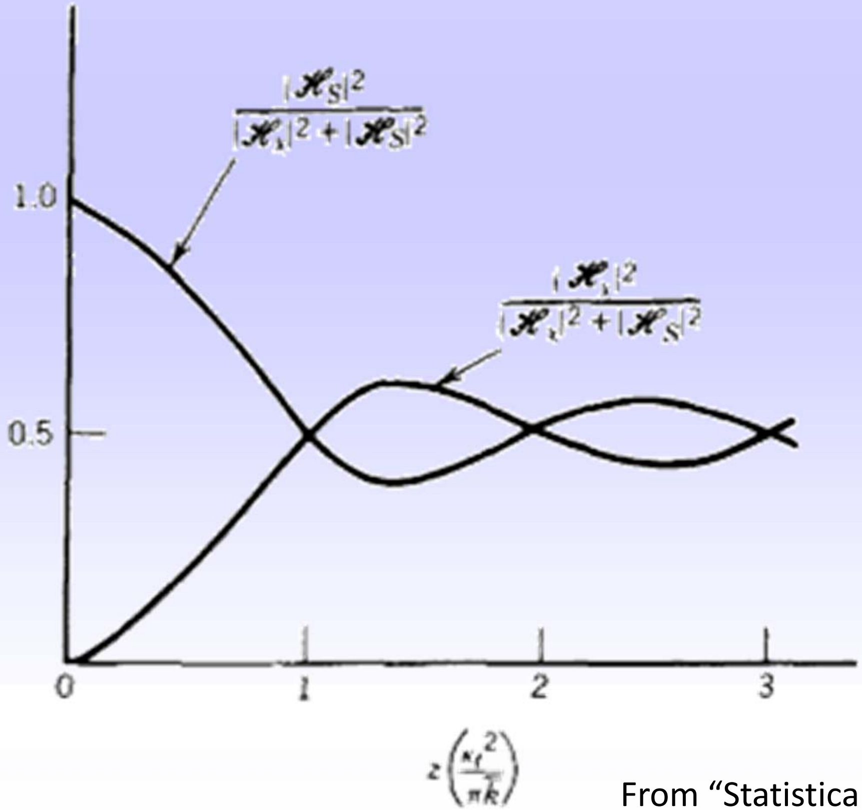


Effects of scintillation due to wavefront propagation are important for V band and high airmass (**Flicker 2001**).



What does theory tell us?

Scintillation arises in optical propagation when turbulence-induced phase aberrations in one region are converted by propagation over long distances to amplitude fluctuations at the receiver



$$|\mathcal{H}_X(\kappa_t;\, z)|^2 = \pi \bar{k}^2 z \left(1 - \frac{\bar{k}}{\kappa_t^2 z} \sin \frac{\kappa_t^2 z}{\bar{k}}\right)$$

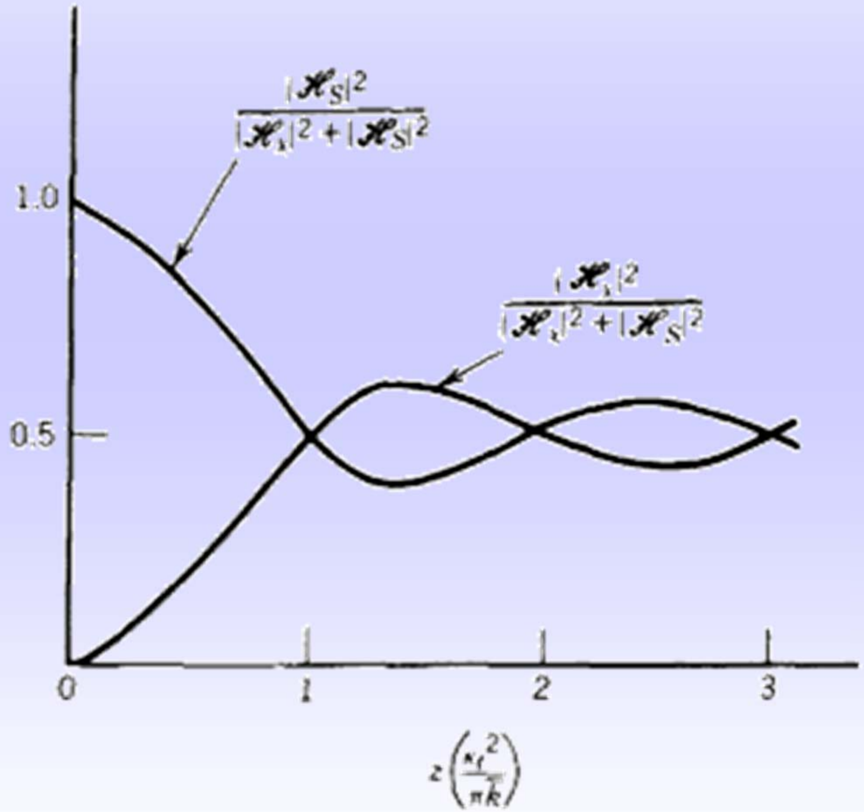
$$|\mathcal{H}_S(\kappa_t;\, z)|^2 = \pi \bar{k}^2 z \left(1 + \frac{\bar{k}}{\kappa_t^2 z} \sin \frac{\kappa_t^2 z}{\bar{k}}\right)$$

$\mathcal{H}_S$: Relative magnitude fluctuation of phase

$\mathcal{H}_X$: Relative magnitude fluctuation of amplitude

From "Statistical Optics" J. W. Goodman, Wiley, New York, 1985

What does theory tell us?



Propagation distance (z)

$z \ll \pi\, k/k_t^2$ $z << r_0^2/\lambda$

negligible amplitude fluctuations

$z >> \pi\, k/k_t^2$ $z >> r_0^2/\lambda$

amplitude fluctuation ~ phase fluctuations

From "Statistical Optics" J. W. Goodman, Wiley, New York, 1985

MCAO Approximations

- Atmospheric turbulence for astronomical observations :

Propagation distances z ~ 100Km

r_0=20 cm λ=500nm => r_0^2/λ ~400Km >> z

According to the theory, scintillation effects can be neglected.
This result contradicts the simulations performed by Flicker (2001) !!!!

- In Solar AO the "guide stars" are not point-like, they are extended objects
- Sensing wavelengths is polycromatic

how critical are scintillations effects?

Simulations with ZEMAX

In order to verify if the correction depends on the DMs sequence, we have designed a simple optical system with ZEMAX

DESIGN:

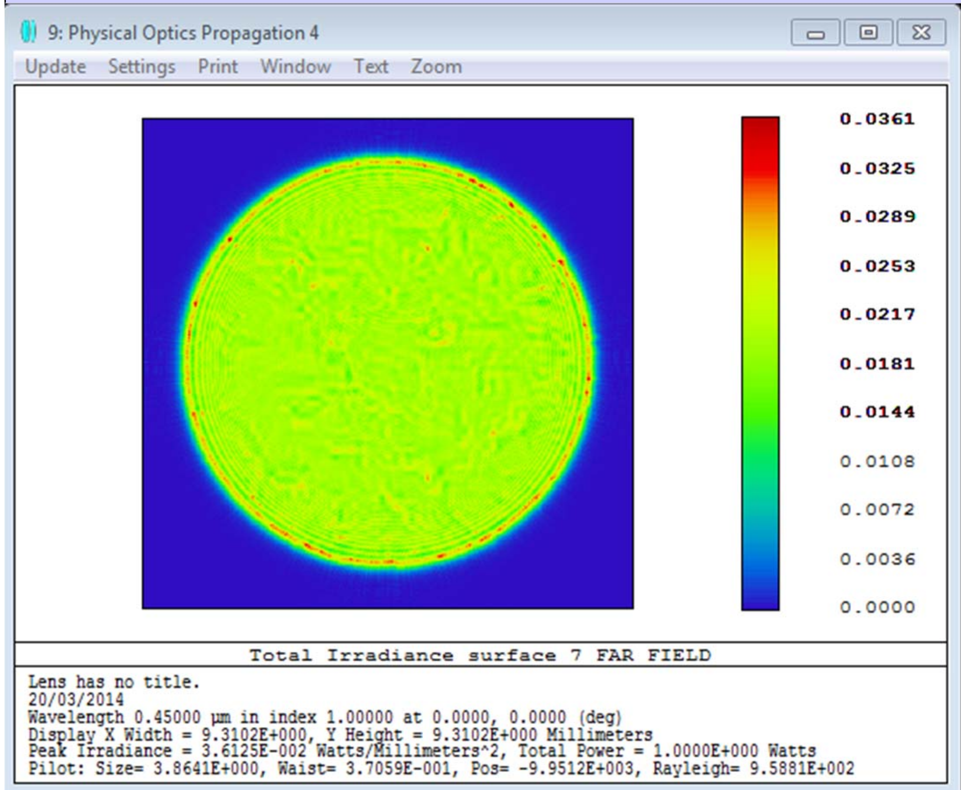
- We simulated two phase screens with IDL using a Kolmogorov model
- We used paraxial optics maintaining constant the size of the pupil (F/12)
- The correction is done by using the same phase screens with opposite sign
- The wavelengths are 450nm,500nm and 550nm

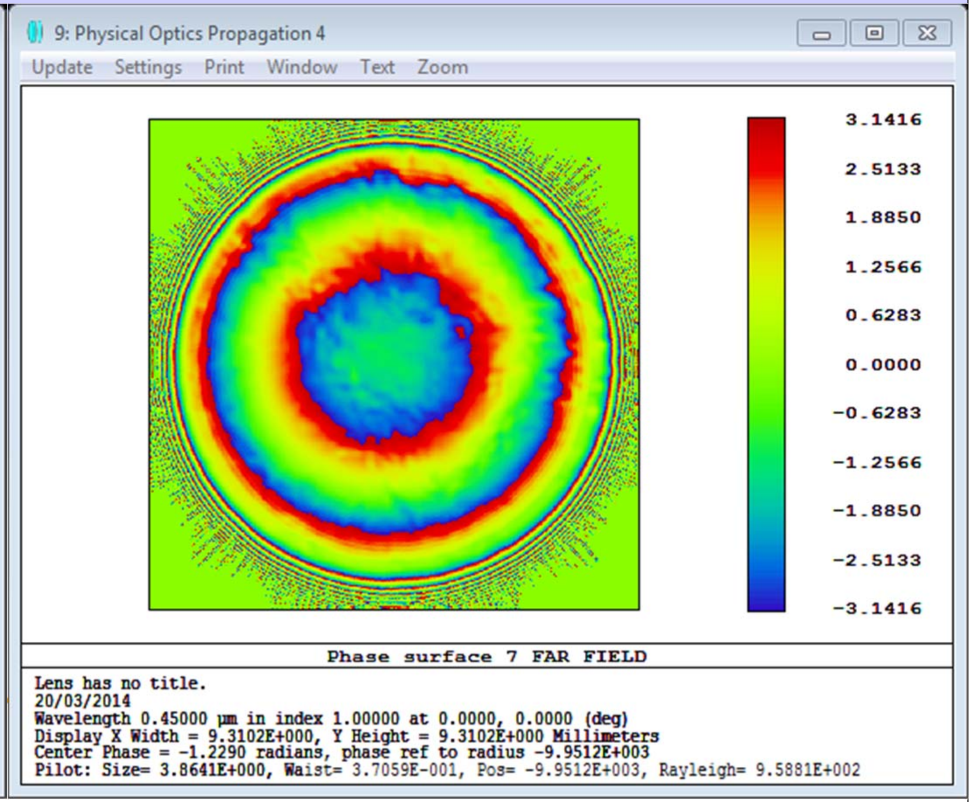
EVALUATION:

- We have used the Physical Optics Propagation (POP) tool to evaluate the wave propagation
- The quality of the image in the focal plane is evaluated with the diffraction encircled energy
- Two cases have been evaluated: large and small phase aberrations

Irradiance and large phase aberration

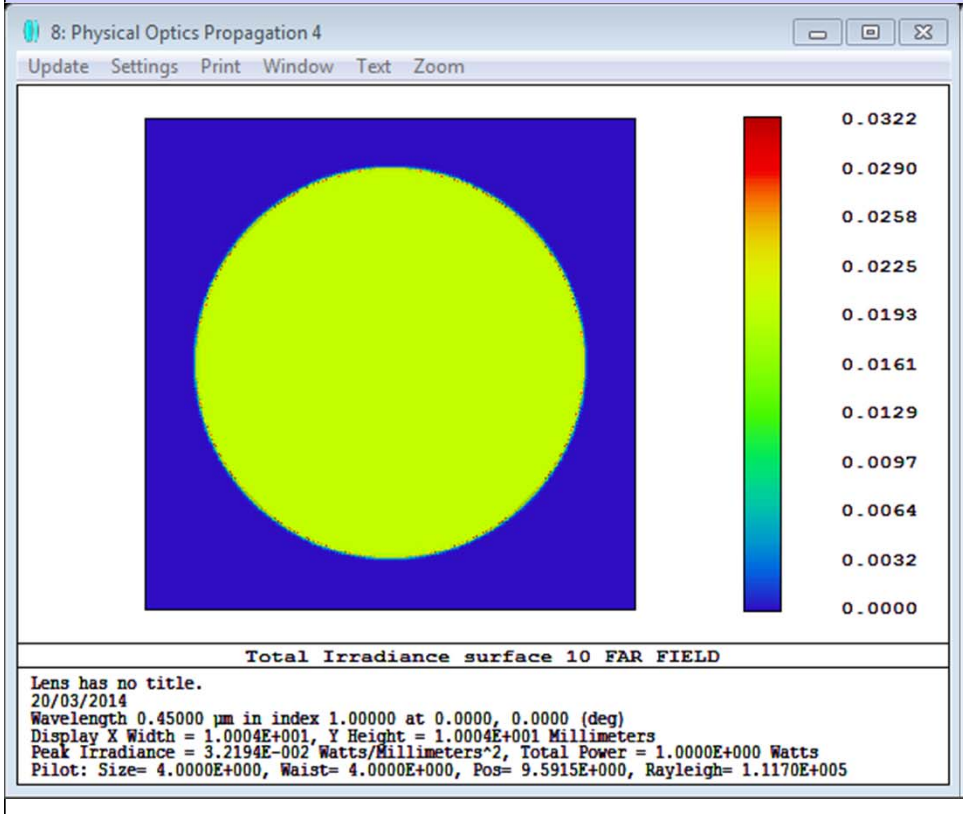
Direct correction,
phase PtV: 5 λ

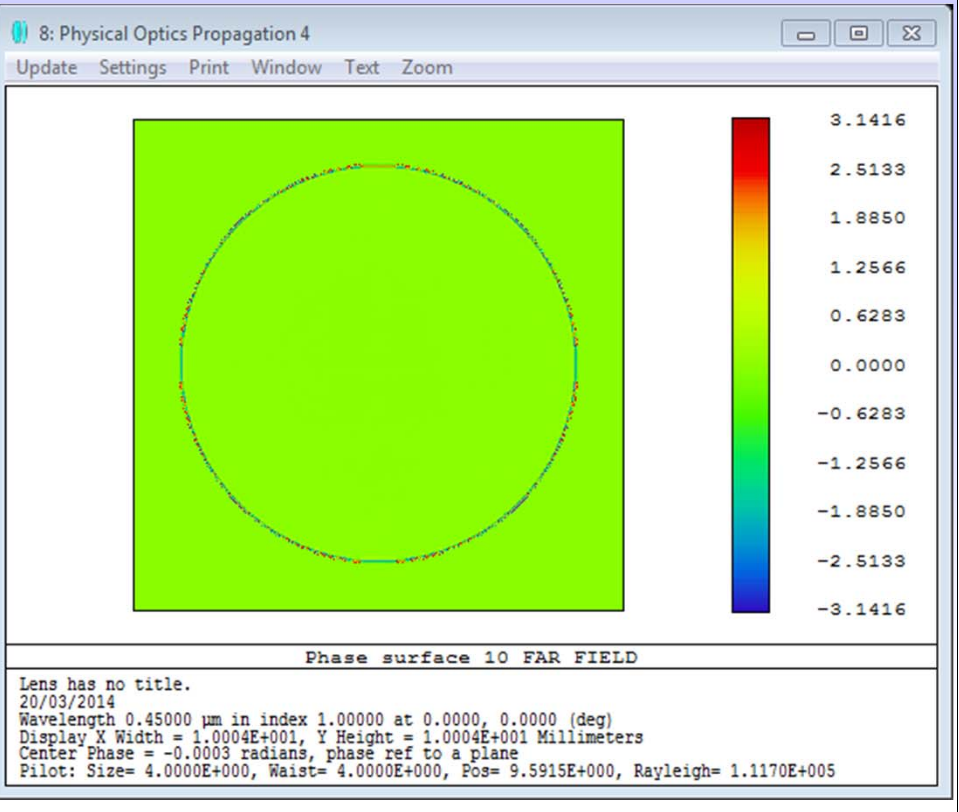




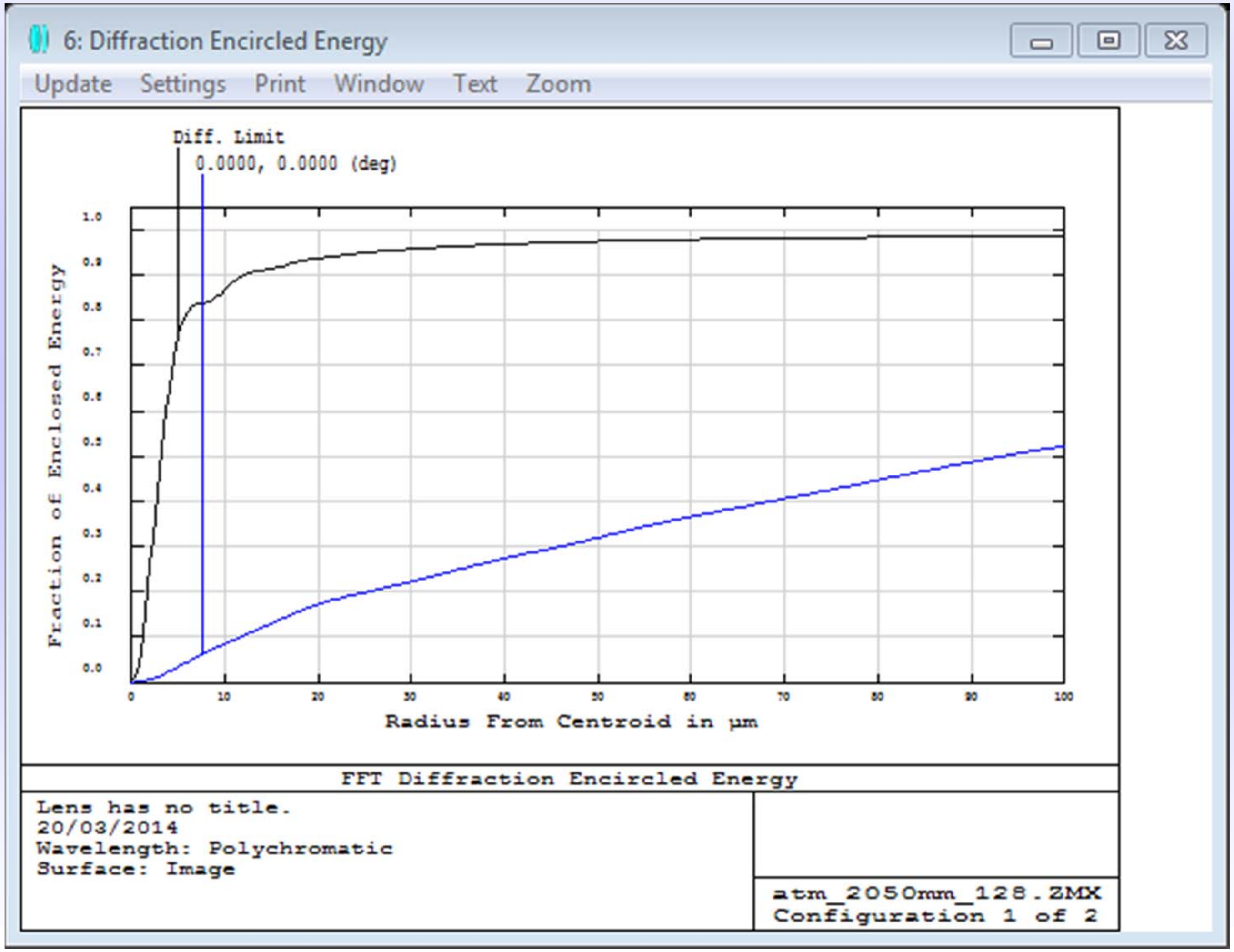
Irradiance and large phase aberration

Inverse correction,
phase PtV: 5 λ



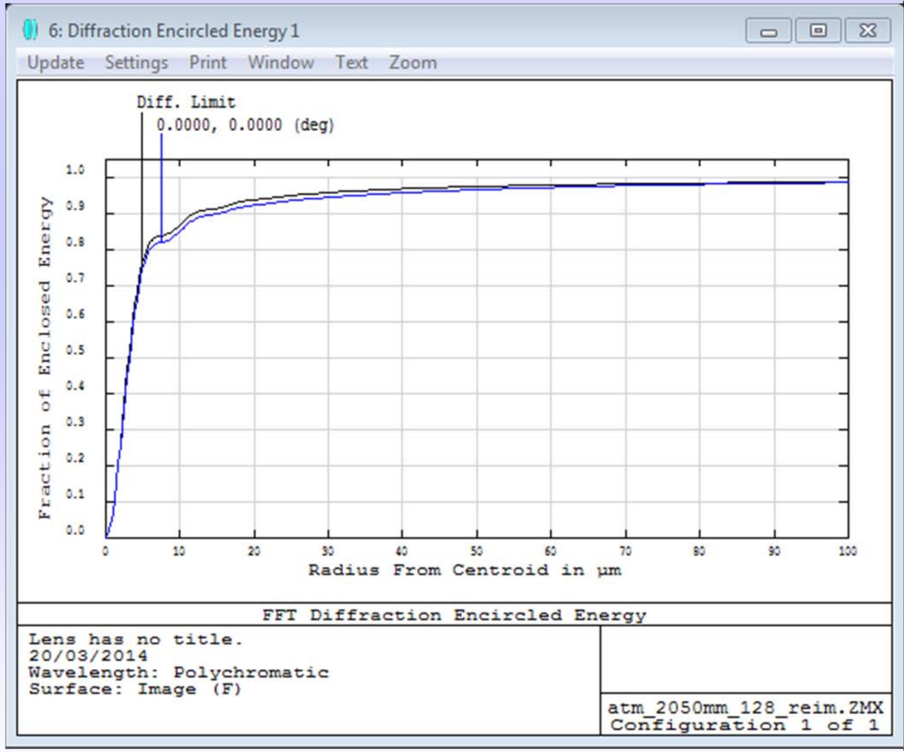


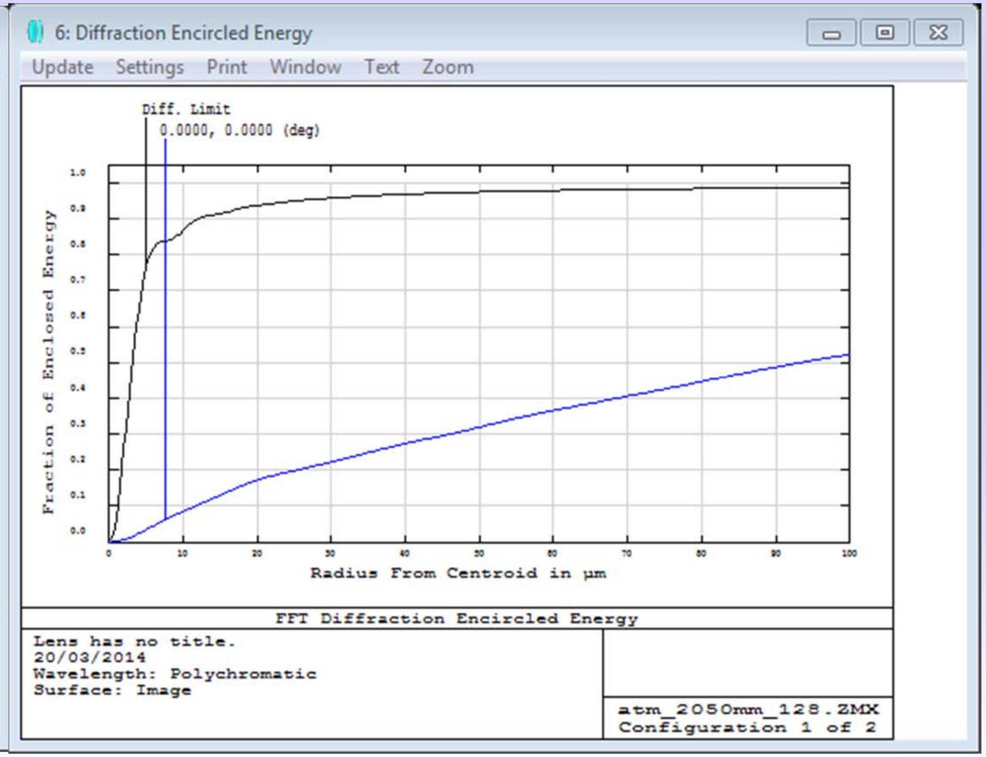
Encircled energy



Encircled energy

Correction in the pupil plane | **Correction out of the pupil plane**

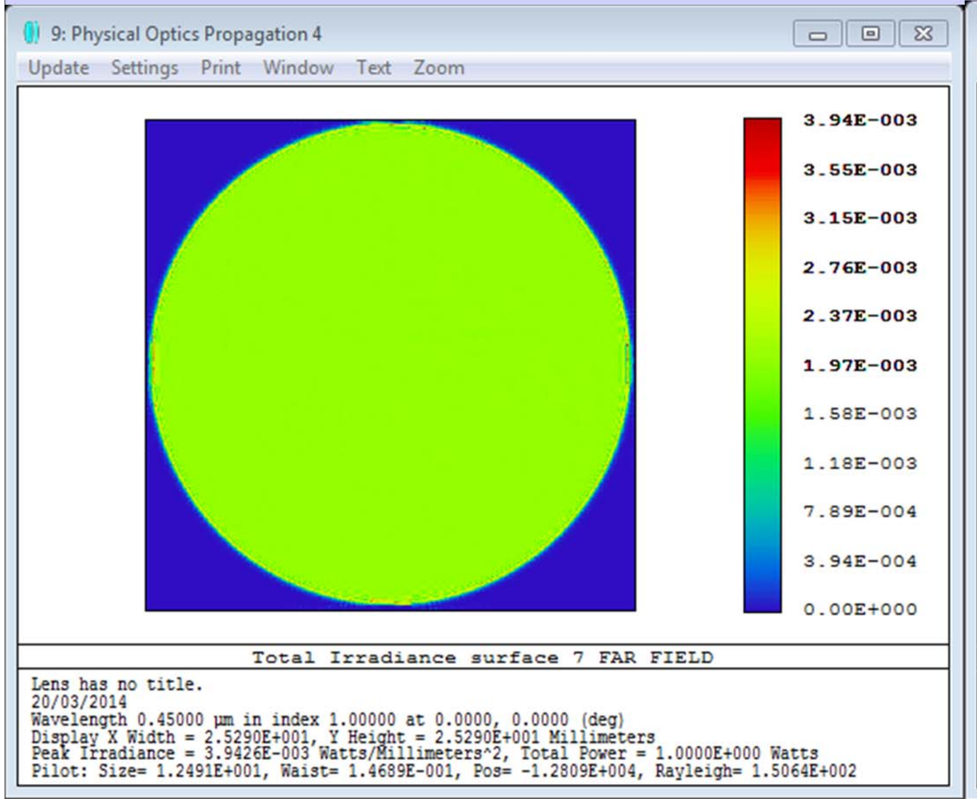


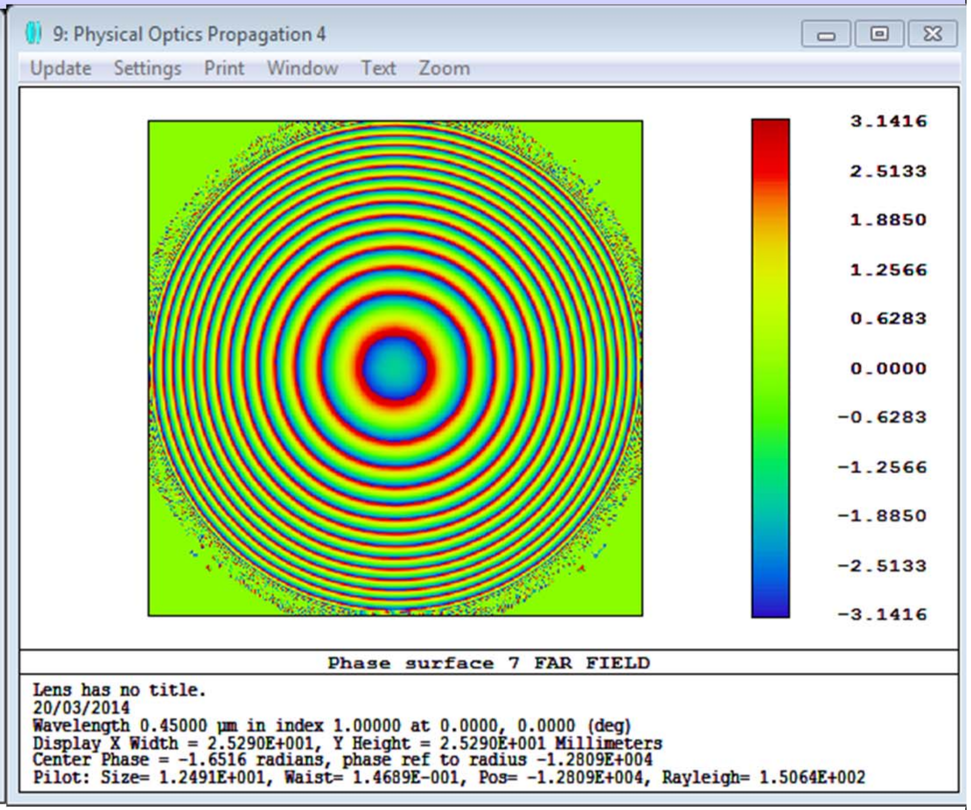


In this simulation the correction of the two layers is limited by the correction out of the pupil plane, phase is so large that rays are out of the field

Irradiance and small phase aberration

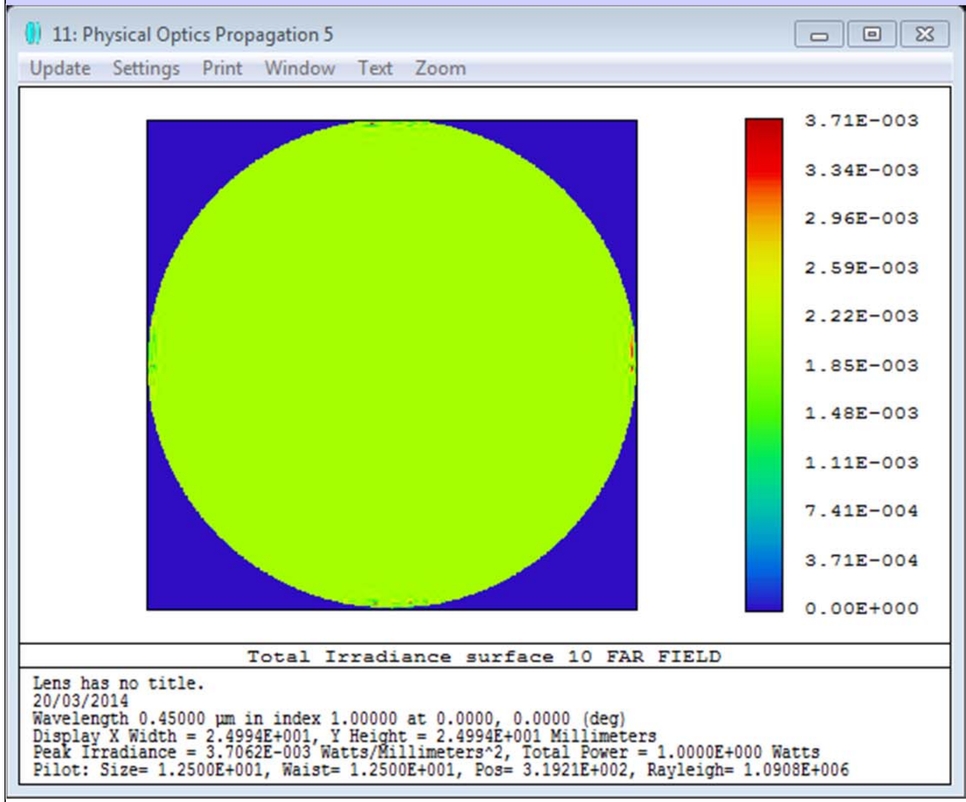
Direct correction,
phase PtV: λ

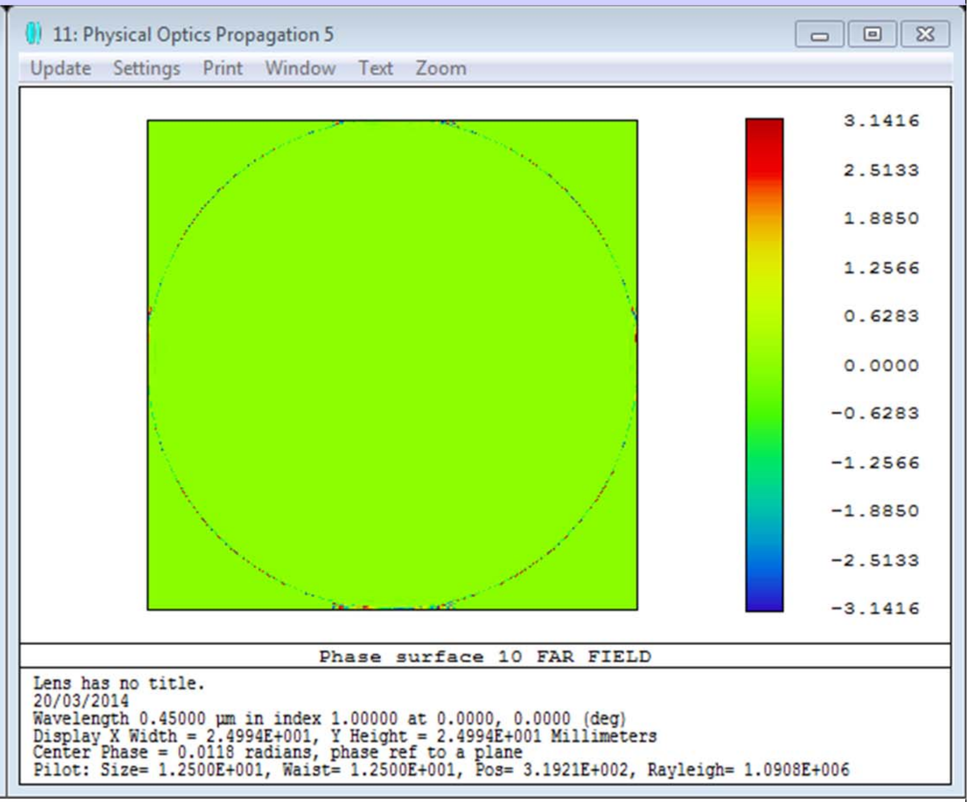




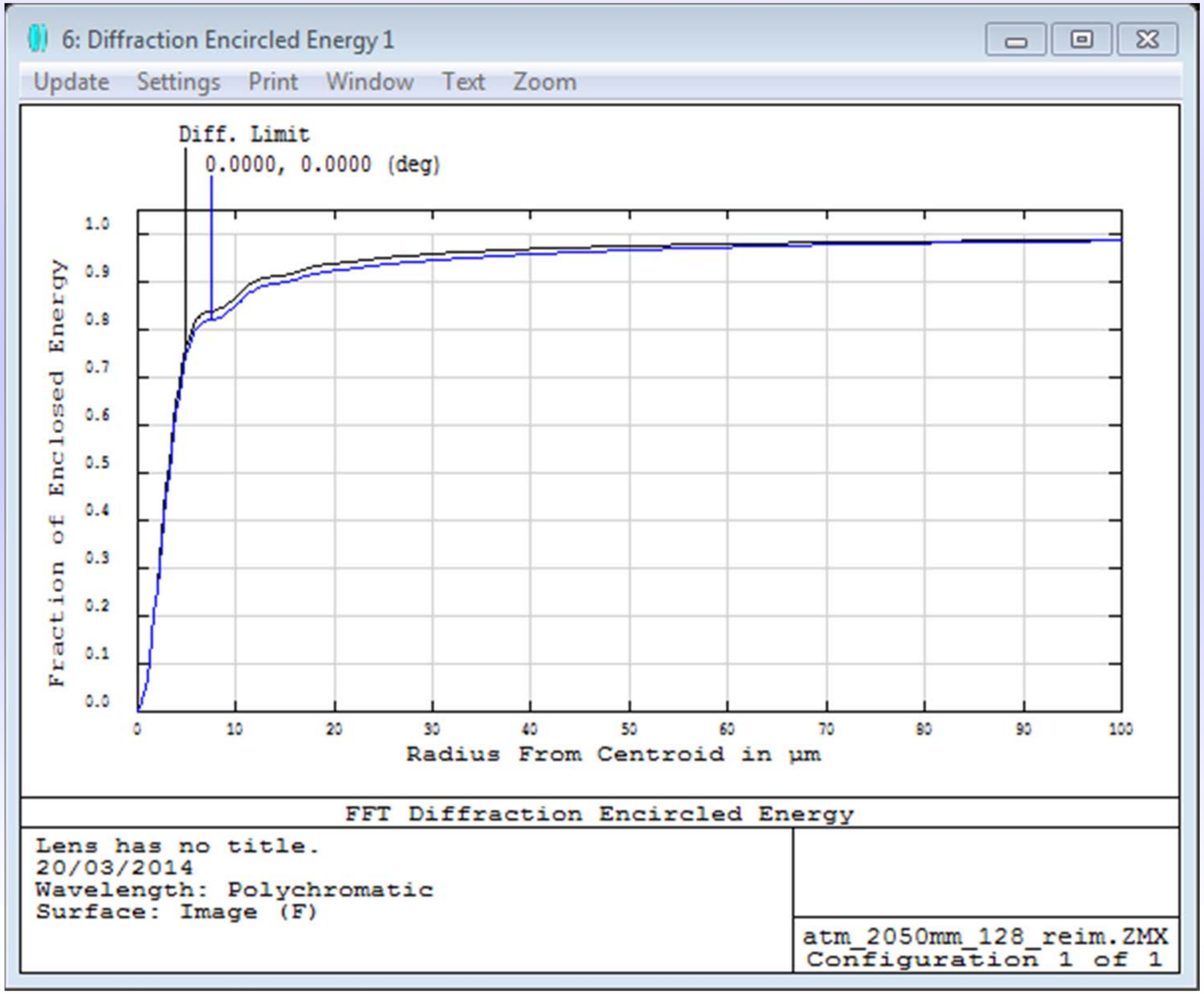
Irradiance and small phase aberration

Inverse correction,
phase PtV: λ





Encircled energy



Conclusions

- Amplitude fluctuations can be cancelled if the correction is done in the inverse order of turbulence layer ocurrence (Flicker 2001)

- Theory of wavefront propagation agreed that amplitude fluctuations are negligible for astronomical observations and therefore the performance of the MCAO system is independent of the sequence of turbulence correction

- ZEMAX simulations have been performed to confirm this theory. However, no clear conclusions can be extracted from these simulations because irradiances are different for the two cases, whereas the encircled energies is the same