Wavefront Corrections for the Detection of Extrasolar Planets using Coronography

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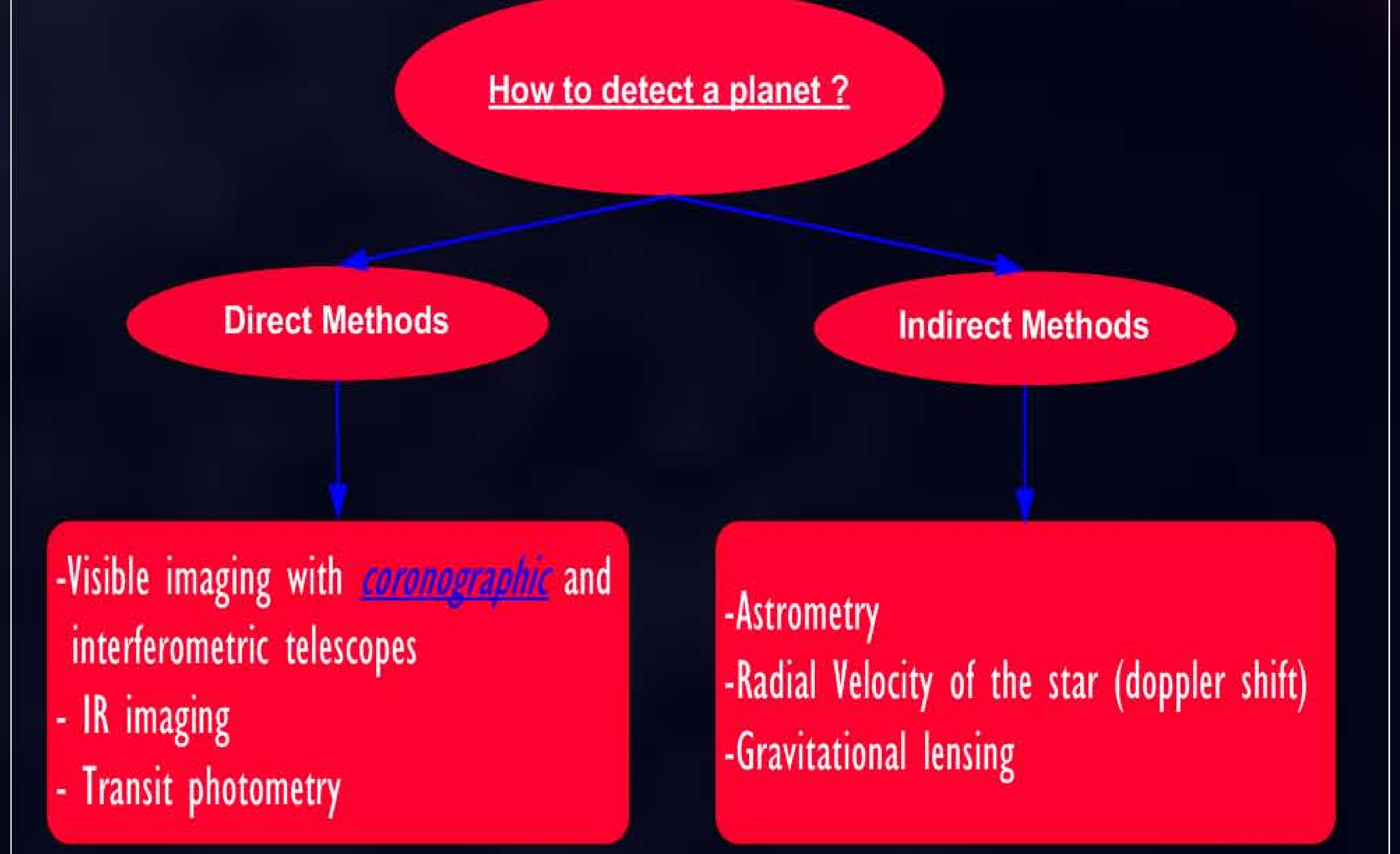
BACKGROUND

Motivation : The ultimate goal of planet finder missions is to find terrestrial planets, carry out an exhaustive physical and chemical analysis of their atmosphere and surface in order to search for potential habitats for life. This requires very high spatial and spectroscopic resolution, which we are far from achieving.

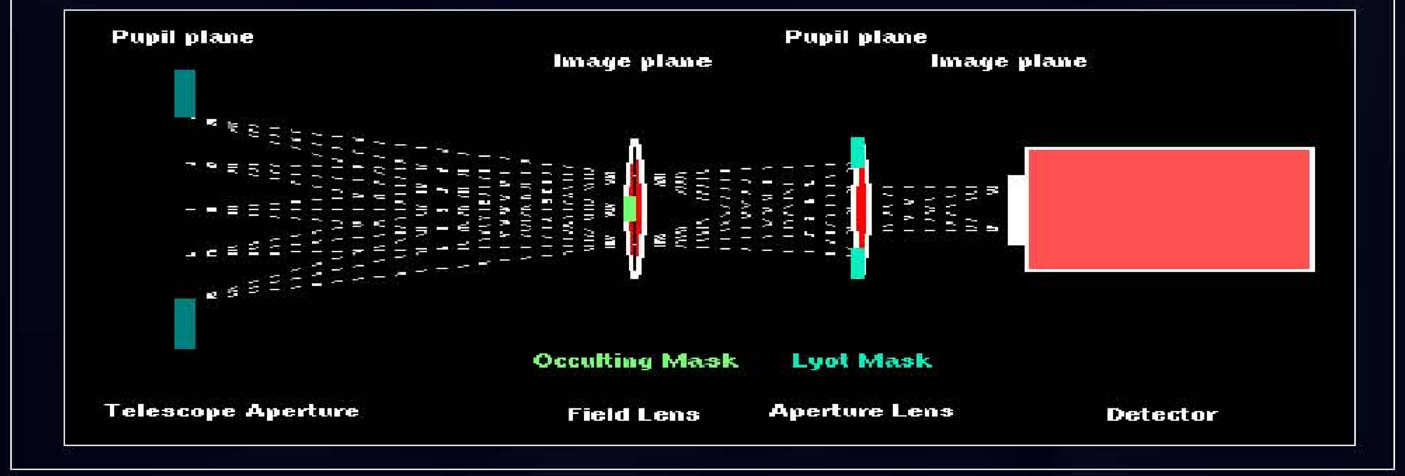
Abstract : Space based coronographic systems for the direct detection of extrasolar planets will require on-board wavefront corrections in order to reach a resolving power high enough to detect faint objects close to bright ones like a planet gravitating around a star. We choose to perform *static wavefront corrections to make the Point Spread Function (PSF) of the mounting as sharp as possible* and reach the required resolving power. Eventually we should be able to reach a wavefront error (WFE) of 2nm.



Coronography Principle

The great idea of coronography is to remove the image of the star by inserting a mask in the center of the beam. The mask reflects the light in the center (image of the star) while passing the light in the side region that may hold a potential planet. Thus the determination of the size of the mask is important.

However, some side lobes of the diffraction stain of the star pass around the edge of the occulter, and mix with the image of the planet. Either a Lyot mask or apodization of the pupil of the telescope is necessary to remove the sidelobes.



First Technical Hurdle : Diffraction

The pupil of the telescope is limited in space and thus is a source of diffraction. The diffraction grating of the star, if not corrected, may overlap the image of the planet making its detection impossible. The detection of a planet requires high accuracy, all the more as the magnitude of the planet is less than a tenth that of the star and that the two objects are separated by only a few arcseconds.

Apodization may be the solution to the problem. An apodization function (also called a tapering function) brings the aperture function smoothly to zero. As the Point Spread Function is the Fourier Transform of the pupil function, the PSF will be sharpened, getting closer to a Dirac. Thus the image of the star and that of a faint object gravitating around it can be separated.

PSF of apodized and non apodized instruments

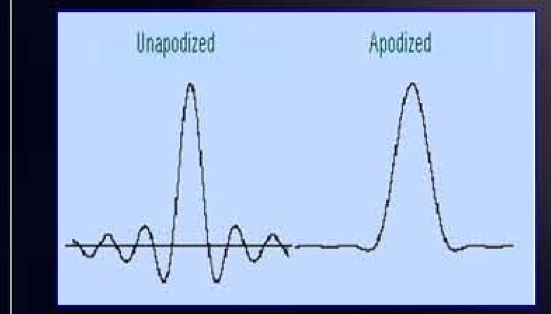
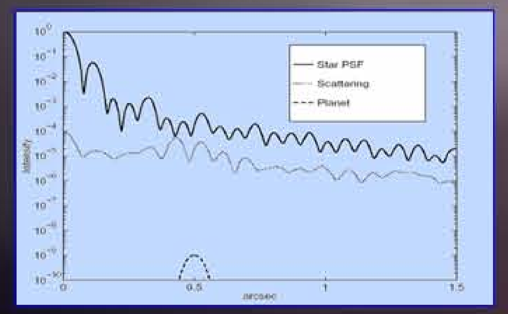
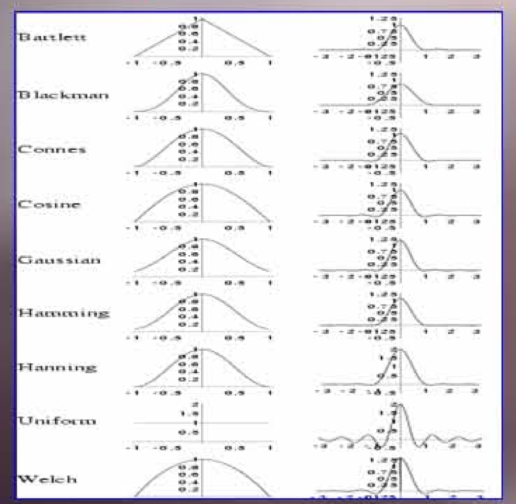


Image of a star overlapping the planet



Apodization functions



Second Technical Hurdle: Wavefront Errors (WFE)

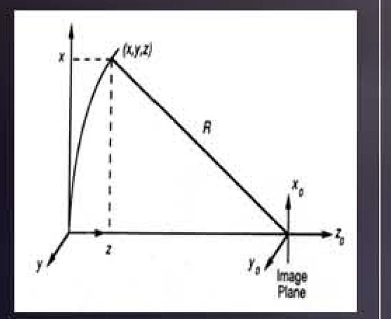
WFE can be brought about by :

- Thermal expansion
- Acoustic and mechanical vibrations
- On earth, atmospheric turbulence
- Optical manufacturing and mounting : Defocus, lateral shift, Angular, transverse and longitudinal aberrations, Seidel aberrations, Astigmatism, coma, spherical aberrations, distortion, scattering due to the roughness, distortion of the optical path due to imperfect flatness of the optics...

Example : Defocus & Lateral Shift

A perfect lens delivers to its exit pupil a spherical wave of radius R whose center of curvature coincides with the origin of the *image coordinate system* (x_0, y_0, z_0). The center is at the origin of the (x,y,z) *pupil coordinate system.*

The equation of the wavefront is $x^2+y^2+(z-R)^2 = R^2$. If x and y are small compared to R (the exit pupil is small compared to the radius of curvature of the wave), and z is sufficiently small so that z^2 can be neglected, the spherical wavefront in the exit pupil can be approximated by a parabola $z= (x^2+y^2)/2R$. Therefore an optical path difference of $W(x,y) = (x^2+y^2)/2R$ in the exit pupil represents a spherical wavefront converging to a point a distance from the exit pupil.

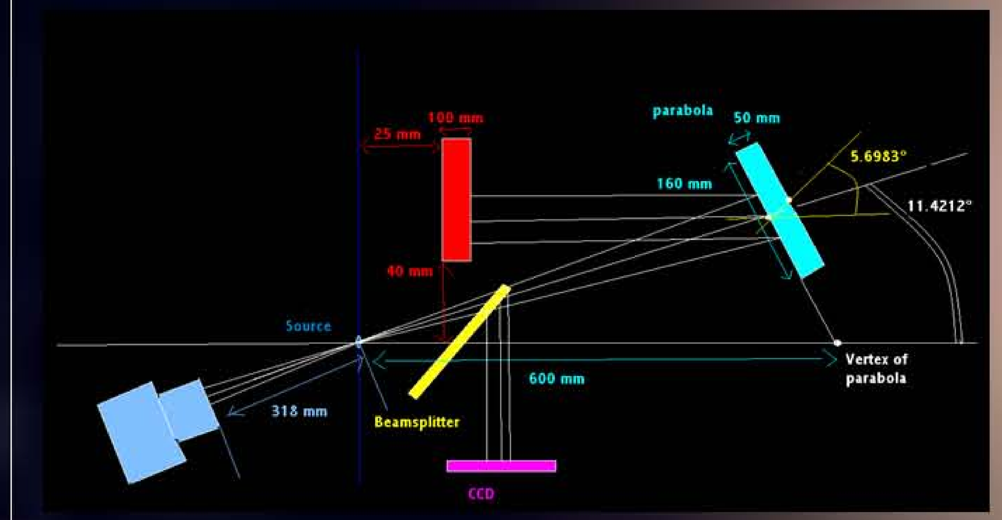


All WFE contribute to decreasing the resolution and the resolving power by making the PSF wider and the sidelobes higher. Thus it is necessary to correct the WFE to sharpen the PSF and be able to detect a planet. Wavefront errors can be computed using softwares like Zemax. It is based on a modeling of WFE by Zernike polynomials.

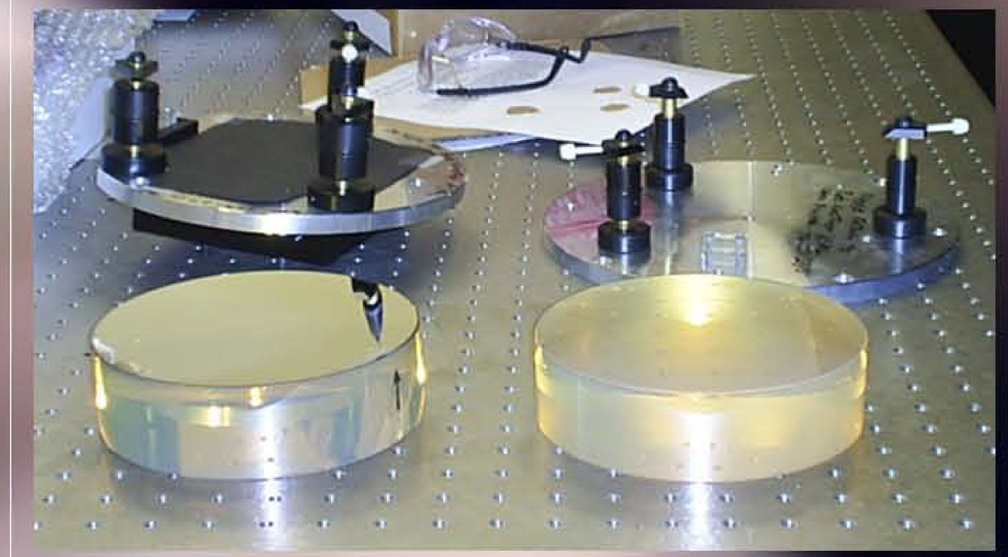
$Z_1 = 1$: piston or bias — $z_6 = \rho^2 \cos 2\theta$: astigmatism x — $z_{11} = 1 - 6\rho^2 + 6\rho^4$: spherical aberration

$Z_2 = \rho\cos\theta$: tilt x — $z_8 = \rho(-2 + 3\rho^2)\cos\theta$: coma x

MY CONTRIBUTION



The mirrors



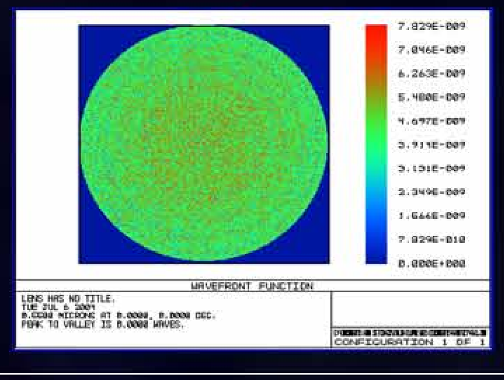
Mounting Principle

Thanks to the software Zemax, we first have to calculate the optical 3D configuration that minimizes the wavefront errors by nulling some aberrations. Zemax will also allow us to analyze independently the effect of a shift or tilt in each degree of freedom on the wavefront. Then a laser based metrology system allows us to place the optical components with a precision of a few nanometers. The rays go back and forth between the parabola and the flat mirror, and end up on the beamsplitter and the CCD. The parabola mirror is called corrector. The wavefront errors it produces are half the inverse of those of the flat mirror. It has been developed by AMSL and tested by Tinsley. The WFE of the parabolic mirror is 6.352 nm, whereas that of the flat mirror is 11.55 nm. However, as the parabola makes up for the WFE of the flat mirror, the WFE of the two mirrors combined is 0.5996 nm. Thus the main source of WFE will be the assembly of the optical components, since the metrology system only allows us to place the components with a precision of 2 nm.

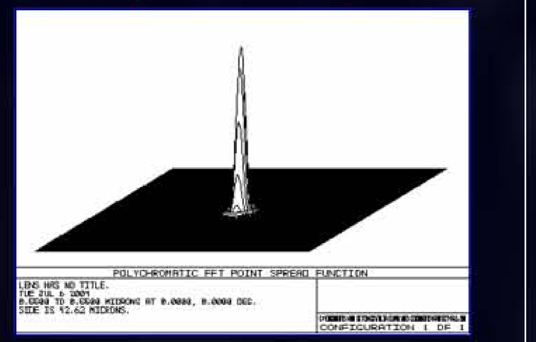
Preliminary results for Zemax simulation

The WFE is 7.83*10-9 waves, which shows that the mounting is theoretically almost perfect. The parabola makes up for the WFE of the flat mirror. The next step will be to compute independently the effects of a tilt or shift in each degree of freedom on the WFE. It will enable us to access the sensitivity of the wavefront to the 2 nm imprecise assembly, performed with the laser-based metrology system.

Wavefront Map



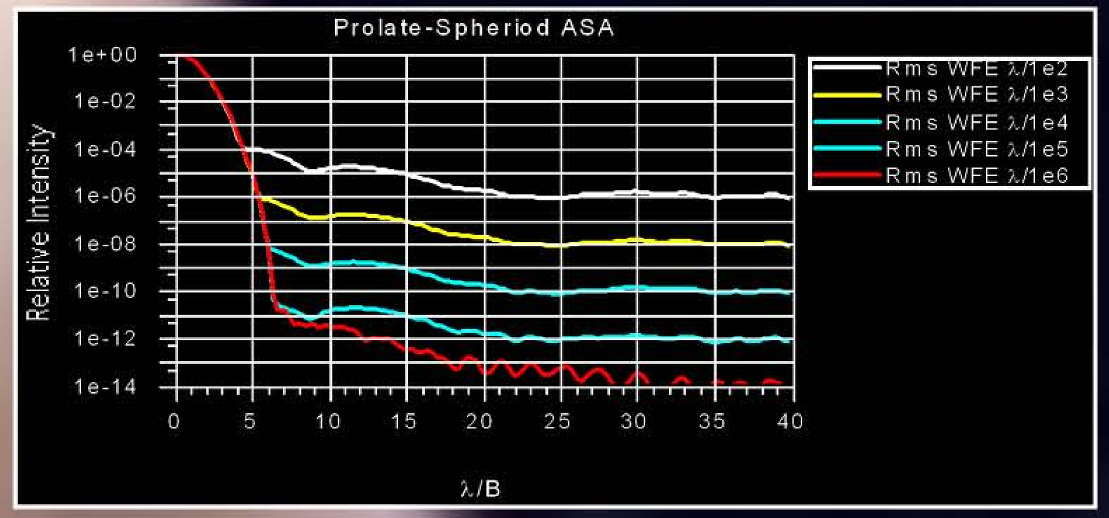
Point Spread Function



Ongoing work

Wavefront nulling will be demonstrated to better than 0.5 nm rms. This will be evident from the reduction in the wings (away from the central core) of the observed point spread functions (PSF) before and after nulling. This will enable a technology demonstration of the technique thereby allowing us to propose it as a viable candidate technology for the upcoming *EPIC (Extrasolar Planet Imaging Coronograph)* proposal. In the future, other missions should be designed and launched to find terrestrial planets and to study their chemical composition, especially the methane ratio which is a sign of possible life. However, our current technology doesn't allow us to reach the required spatial and spectroscopic resolution.

Expected PSF



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