High-contrast Coronagraph Development in China for Direct Imaging of Extra-solar Planets

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High-contrast Coronagraph Development in China for Direct Imaging of Extra-solar Planets

Outlines

1. Scientific motivation
2. Coronagraph Development (Theory & Design)
3. Coronagraph Laboratory Test
4. Ground-based Imaging
5. Space-based Imaging
6. Conclusions & Future Development

1. Scientific Motivation

374 exoplanets have been found mostly by using indirect detection methods, including

- Radial velocity or Doppler method: measure the speed variation of a bright star with respect to the Earth (Most popular technique).

- Transit method: If a planet crosses in front of its host star, then the observed brightness of the star will change (Waiting for the rabbits!).

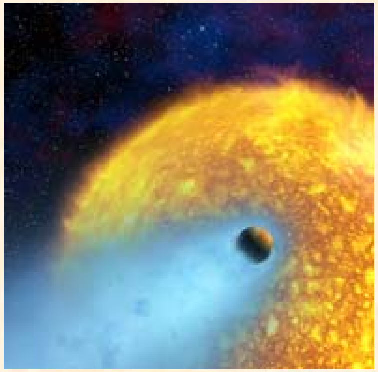
- Gravitational Microlensing : potentiality to detect lower mass exoplanets.

http://planetquest.jpl.nasa.gov/

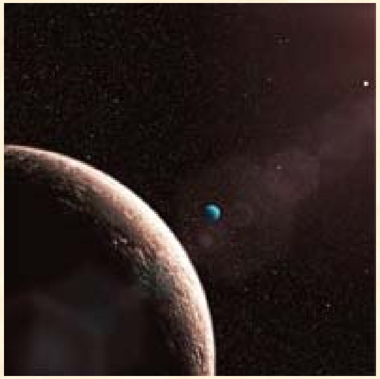
1. Scientific Motivation

From NASA

Some interesting discoveries



HD 209458 : Together with transiting approach, the radius and mass ($1.42R_J$, $0.69M_J$) of the planet orbiting are firstly determined (Henry et al. 2000).



GJ581e: the lightest exoplanet $M_{min}=1.9M_{\oplus}$ (M. Mayor et al. 2009. 04. 21)

GJ581d: located in habitable zone area **(Lucky brother unlucky!)**

CoRoT-7b : rocky planets M=4.8M , ρ =4.3~6.9 g/cm^{-3}

$\rho_{\oplus}$ =5.52 g/cm^{-3}

(D. Queloz et al. 2009).

Recent exoplanets discovered through direct imaging method

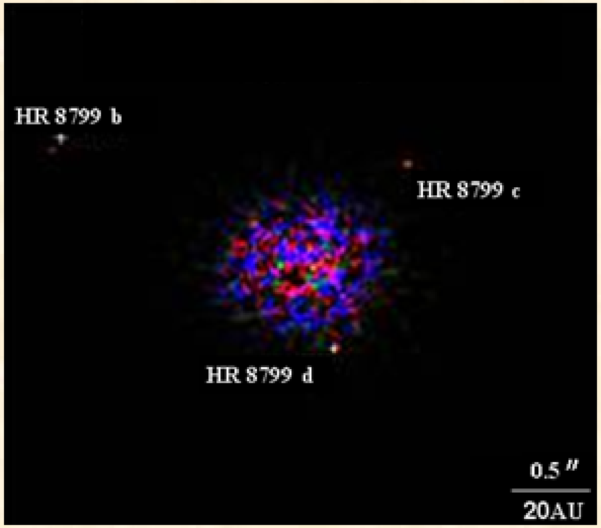
(Conventional Lyot Coronagraph)

Gemini/Keck
Ground-based

HST
Space-based

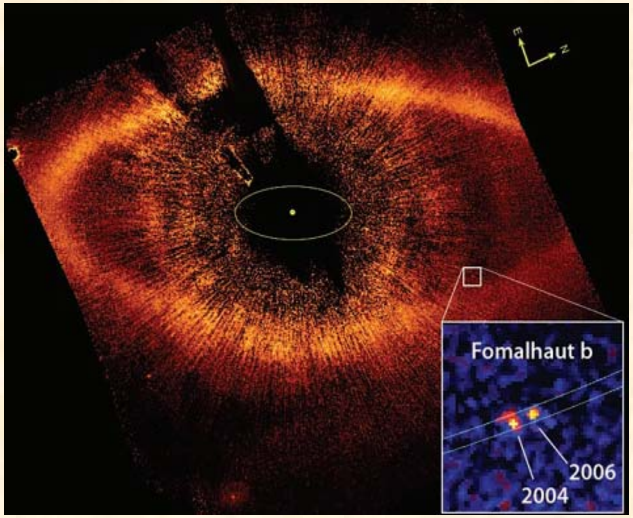
VLT
Ground-based

HR 8799 Planetary system



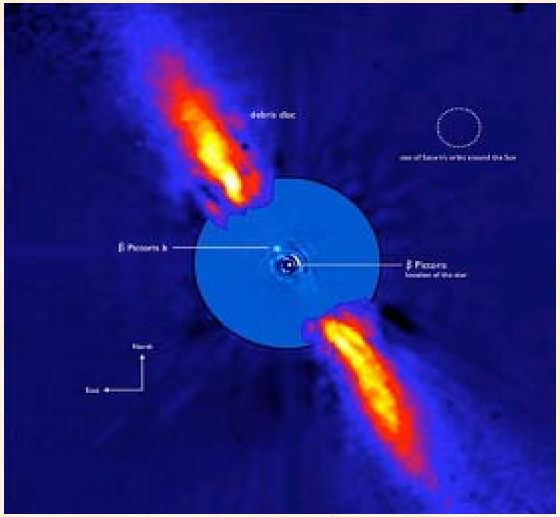
Christian Marois et al. 2008

Fomalhaut b system



Paul Kalas et al. 2008

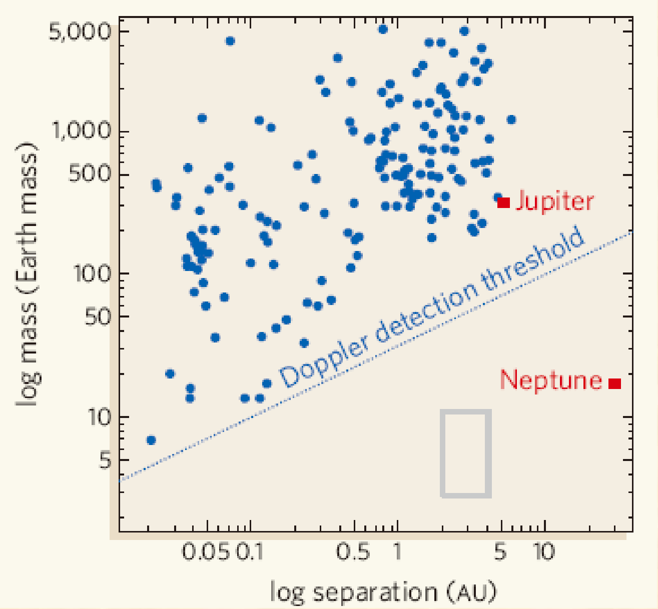
β Pic b system



A.-M. Lagrange et al. 2009

Limitation of the current indirect detection approaches

- Either quite massive ($0.16M_J < M \sin i < 13M_J$) or very short orbits (0.03-4 AU) . A recent numerical simulation (Ida and Lin 2004.) suggests that many planets should have a size similar to Earth and Jupiter, with long-period orbits (Ida and Lin 2004).
- Mass ambiguity: ***M sin i*** (***i*** is the declination angle).
- Cannot perform spectroscopic measurement and therefore cannot determine another Earth.



Didier Queloz, Nature, 2006(439):400-401

Scientific Goals:

Short term goal:

- The coronagraph should reach a contrast of 10^{-6}~10^{-7}

Long term goal:

- The coronagraph should reach a contrast of 10^{-10}

Two working modes:

1) The search mode (image) includes determining quantities such as separation, position, orbital parameters, and mass.

2) The characterizing mode (spectroscopy) would allow us to answer the question “whether life exists on other worlds” – one of the most fundamental questions in science.

Observation:

We proposed to develop a coronagraph for exoplanet imaging, with the scientific cases focused on three aspects:

1)As a following up observation of the indirect detection, we will image some of the 374 known exoplanets and measure the important physical parameters that current techniques cannot perform.

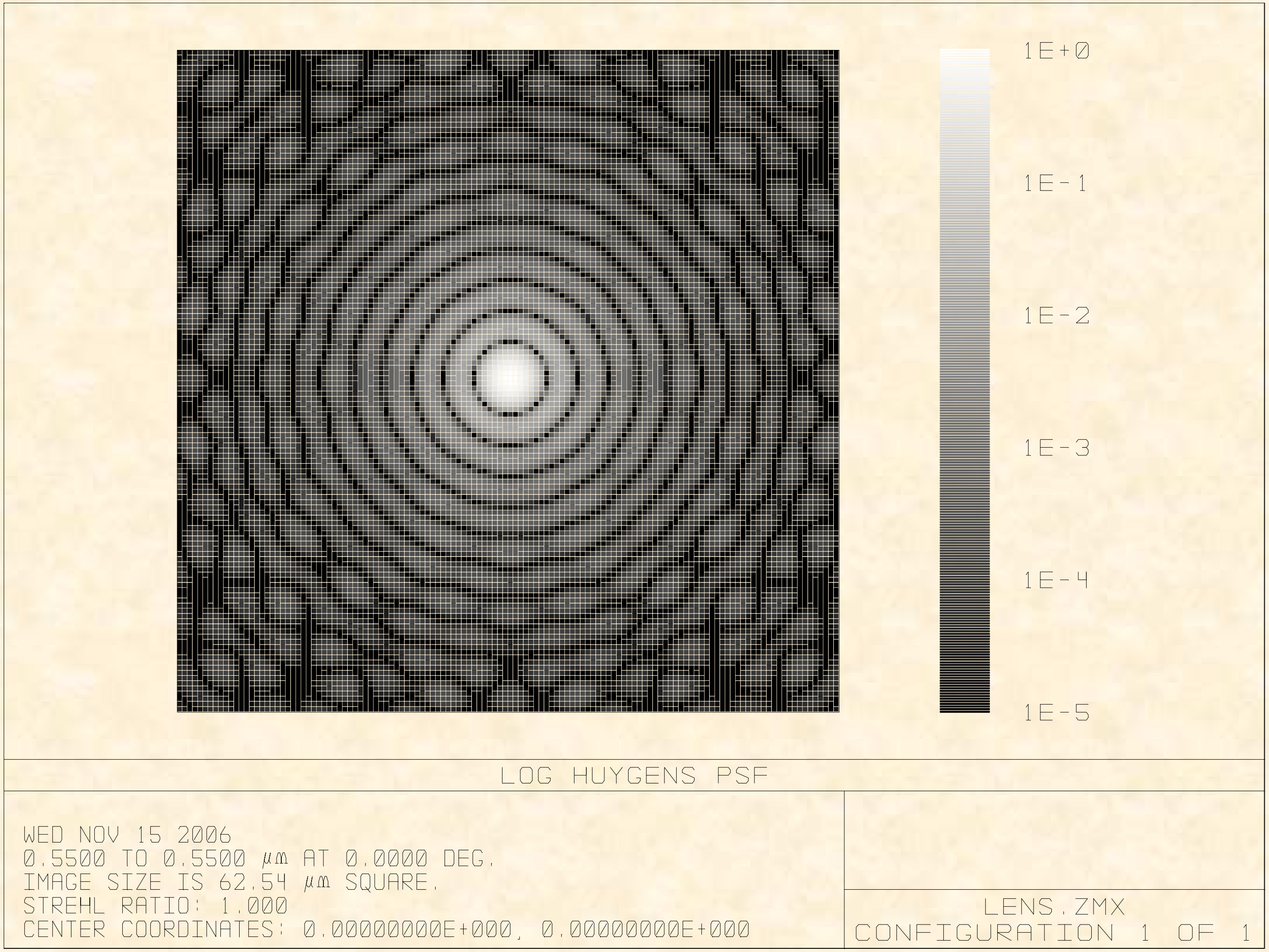
2)Direct imaging of young giant massive planets that only need a contrast in the order of 10^{-4}~10^{-6} (Marley, Mark S. et al. 2007, Wuchterl, G. 2000).

3) Be able to direct detect Earth-like planets with life signals.

2. Coronagraph Development

(Theory and Design)

Direct Imaging: How to remove the star diffraction light?

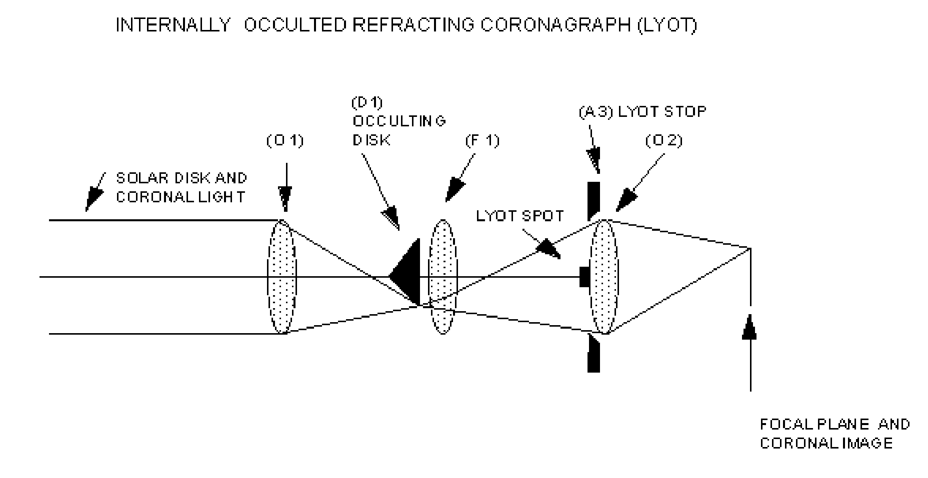


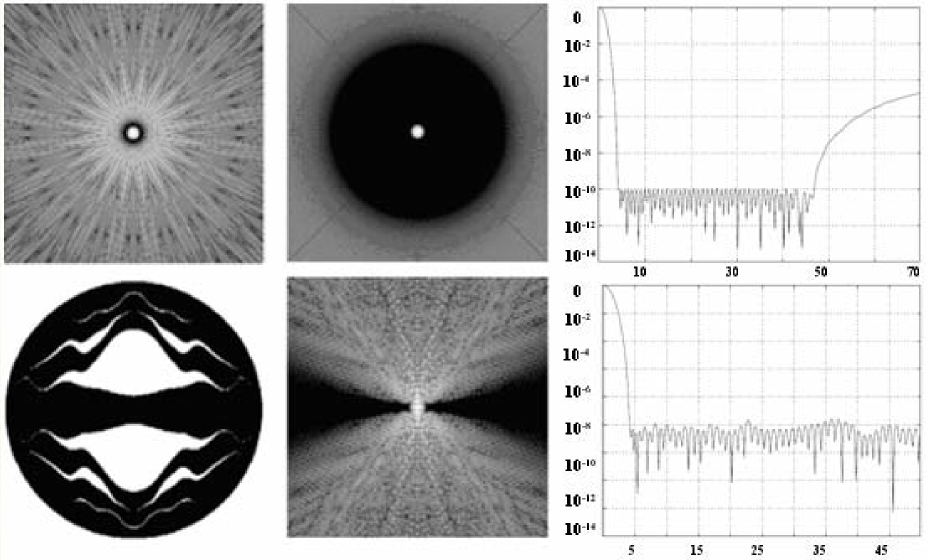
Direct Imaging: How to **remove** or **attenuate** the star diffraction light?

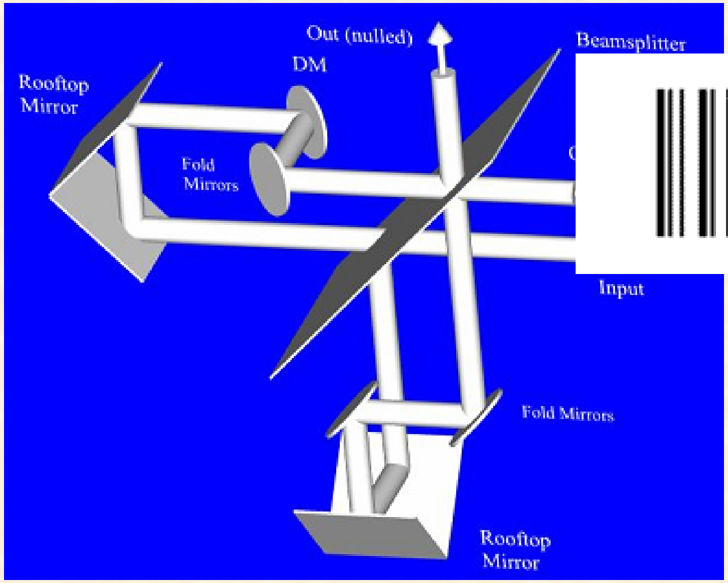
Lyot Coronagraph

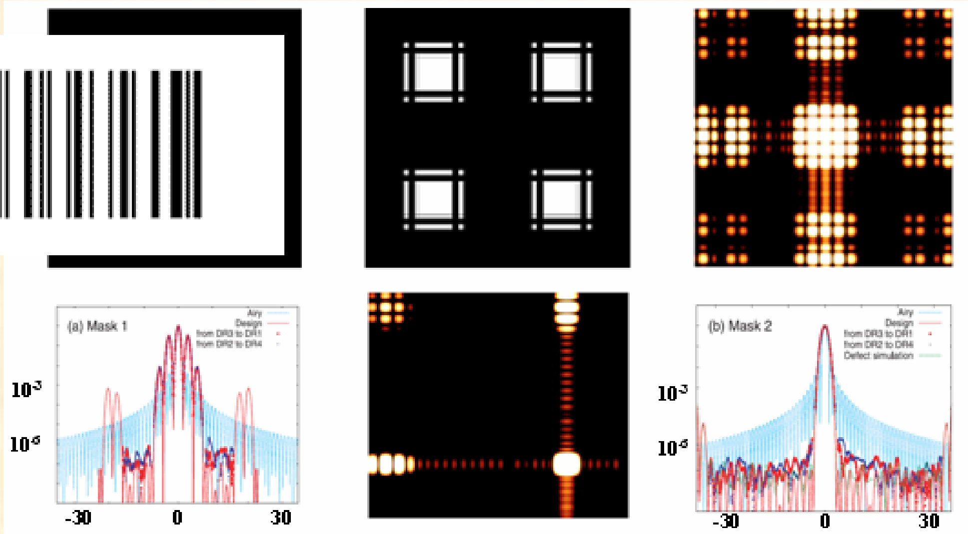
Interferometric nulling Coronagraph

Shaped-pupil Coronagraph







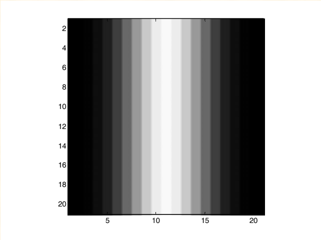


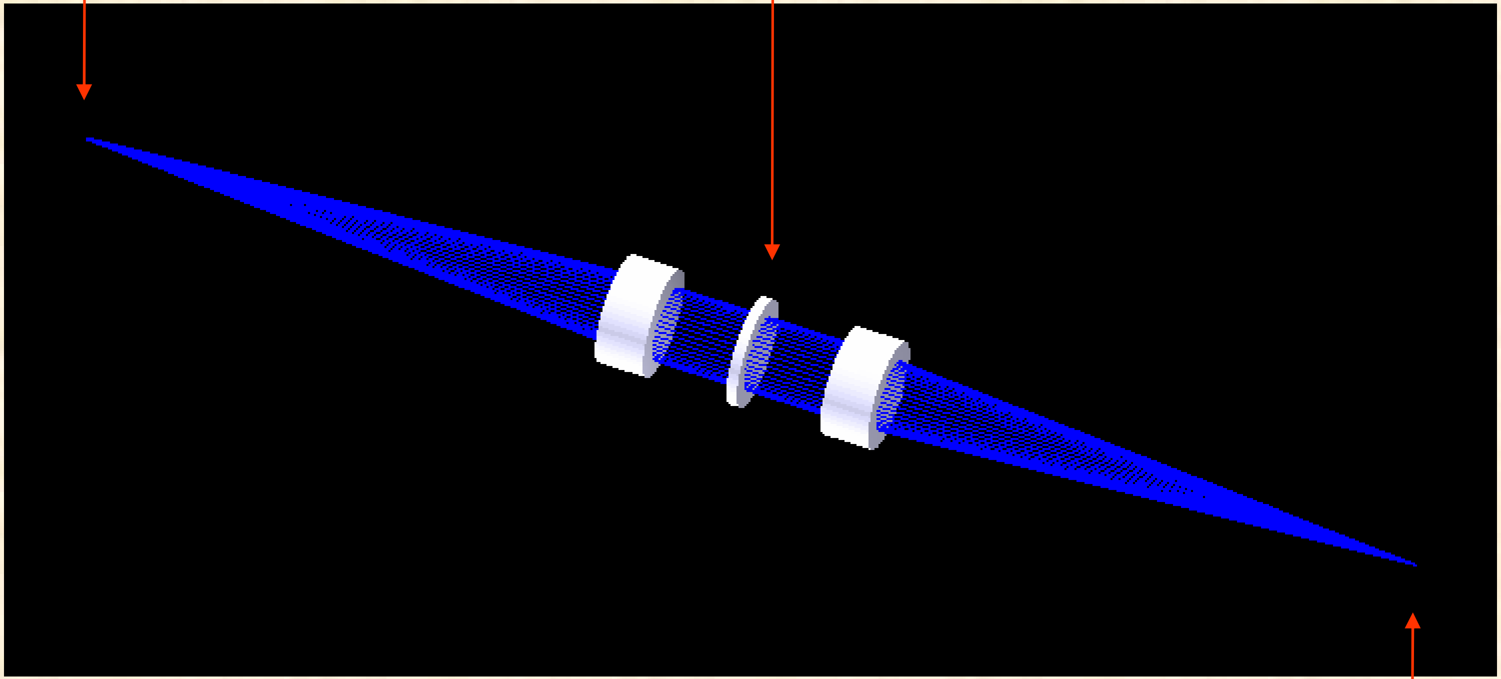
Guyon O., Pluzhnik E. A., Kuchner M. J., et al., AAS, 2006(167): 81-99

Layout of the Coronagraph System

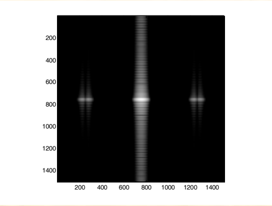
Telescope Image

Step-transmission Filter,
on pupil plane





High-Contrast Image
On image plane



2.1. General Requirements for the Coronagraph

Three High: Contrast +Angular resolution &Throughput.

For direct imaging of exoplanets, a coronagraph must provide high-contrast image:

- Contrast: for young giant planets: $10^{-6} \sim 10^{-7}$ (short-term goal)
  for earth-like planets: $10^{-9} \sim 10^{-10}$ (long-term goal)
- Wavelengths: visible, near infrared or mid-infrared .
- Planet to star angular distance :
  10 PC: 4 λ/D at VIS (0.05 ") for a 8-m telescope

The flux ratio of Exoplanet and Star at 10 PC with 0.05" separation is 10^{-7}, according to a benchmark model (Brown & Burrows 1990).

2.2. Coronagraph for Exoplanet Imaging: Principle

Point Spread Function (PSF)

The electric field of the light wave at the pupil plane can be expressed by a complex number

$$E(u, v) = P(u, v)\, e^{i\Phi}$$

where *P (u ,v)* is the so-called pupil function;

The Point Spread Function (PSF) at the focal imaging plane is the square of the Fourier transform of the E field,

$$I(x, y) = \left| \iint_{-\infty}^{+\infty} E(u, v) e^{i(xu+yv)} du dv \right|^2 = \left| \vec{F}[\ E(u, v)\ ] \right|^2,$$

See Guyon, et al.2006, ApJ, 167, 81 for Different high-contrast coronagraph

2.3. Step-transmission Filter Coronagraph

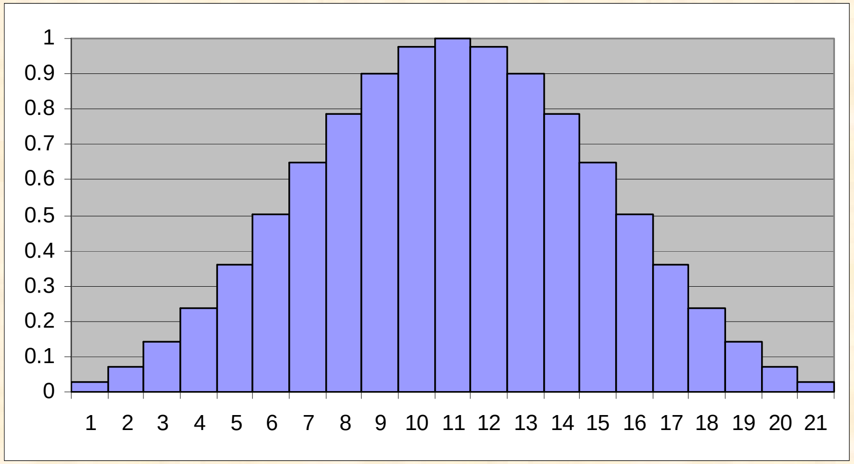
(Ren & Zhu 2007, PASP, 119, 1063)

Coronagraph:

The coronagraph consists of one or two identical transmission filters perpendicular with each other, so that the diffraction of light is suppressed in two directions.

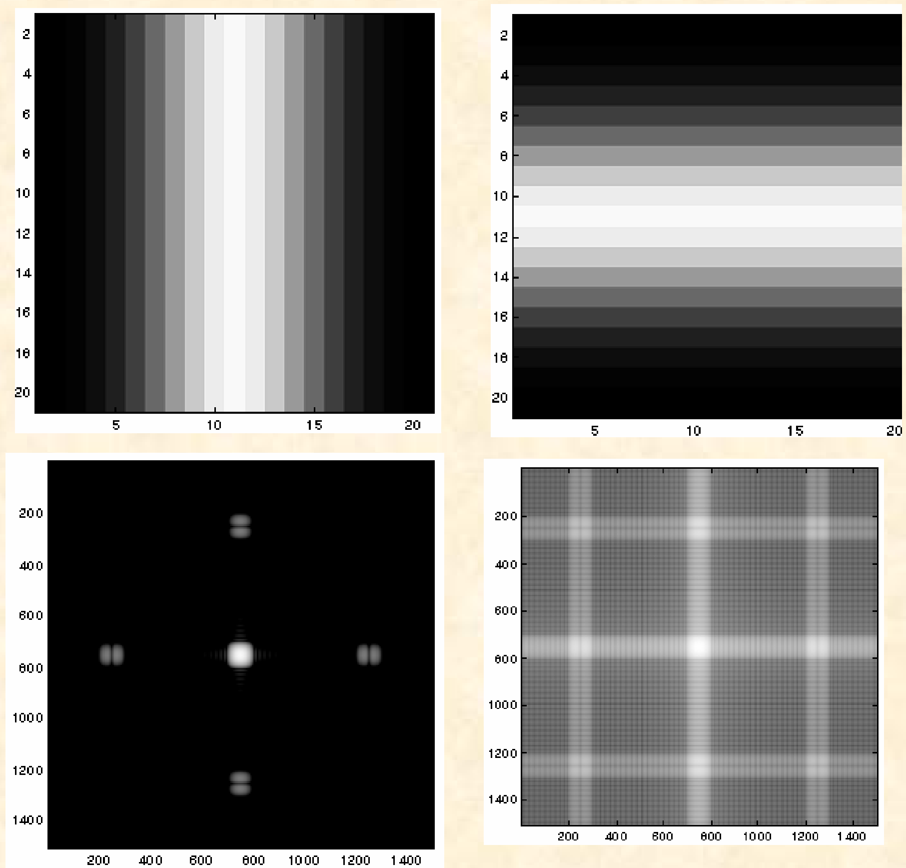
Each transmission filter is composed of finite number of transmission steps.

Transmission of a filter with 21 steps.



Case 1: 21-step transmission filters (throughput=14.5%)

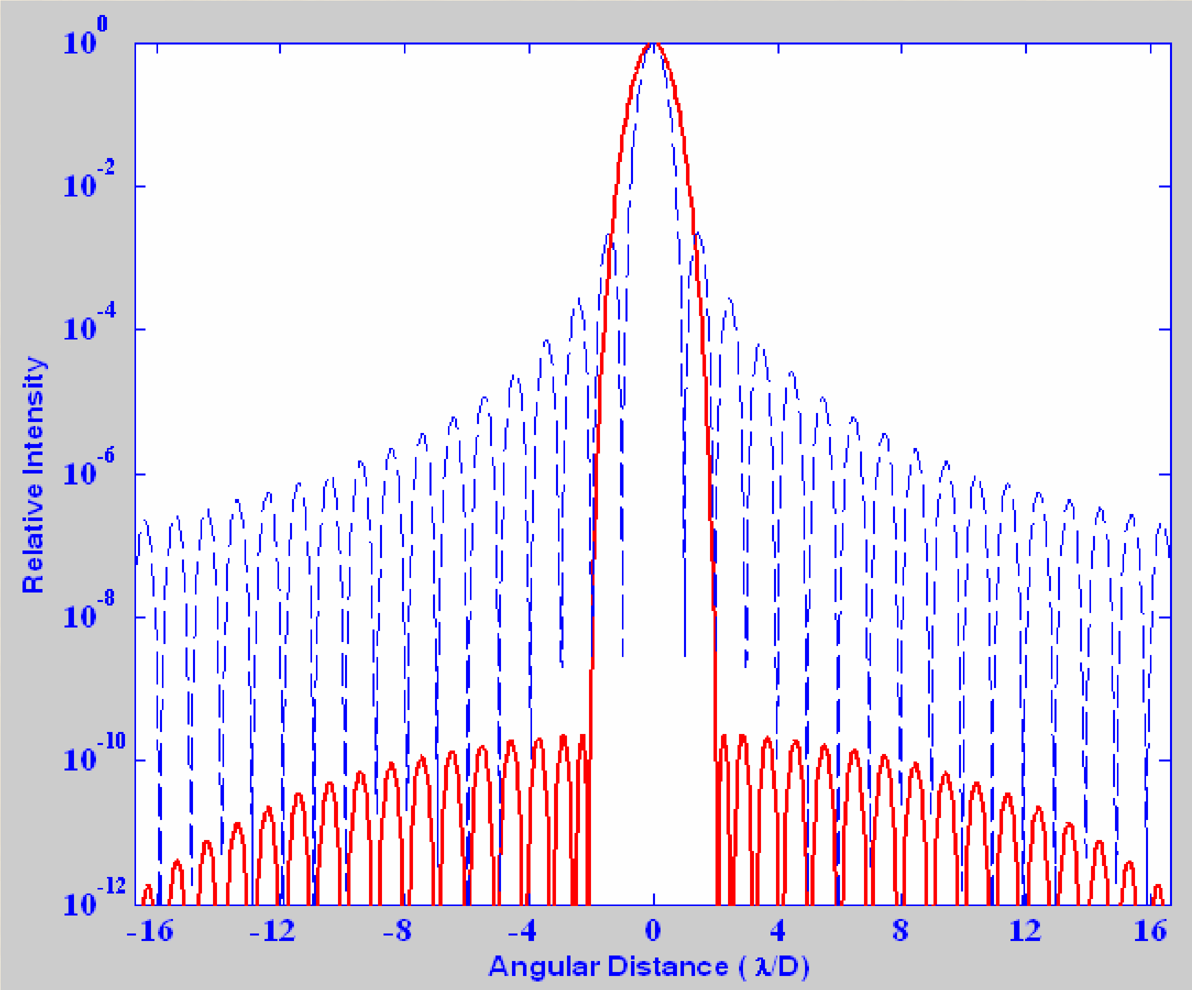
Transmission Pupil: consists of two identical transmission filters.
In each filter, transmission changes only in one direction.



PSF at the focal Image Plane (Two filters)

Case 1: 21-step transmission filters (throughput=14.5%)

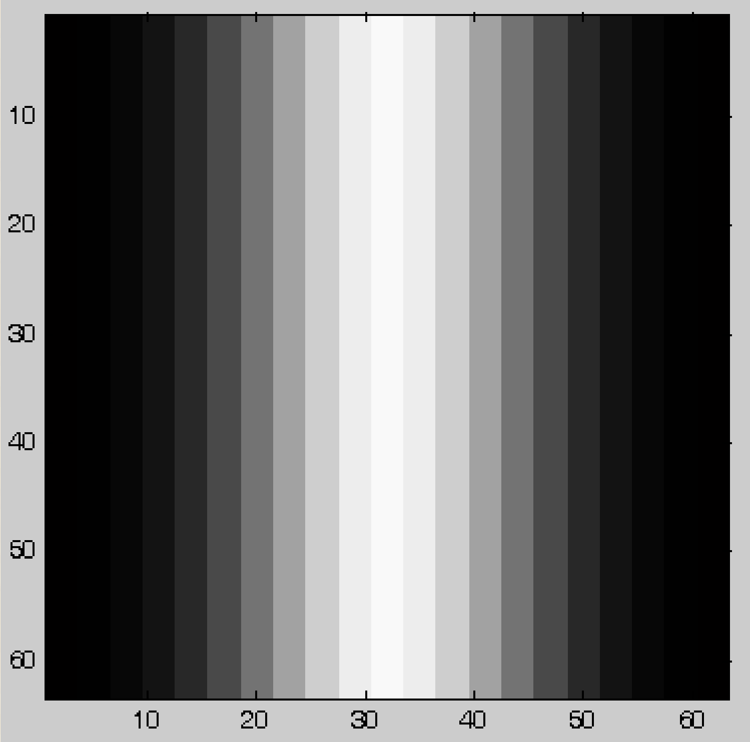
Theoretical Performance (Two filters)

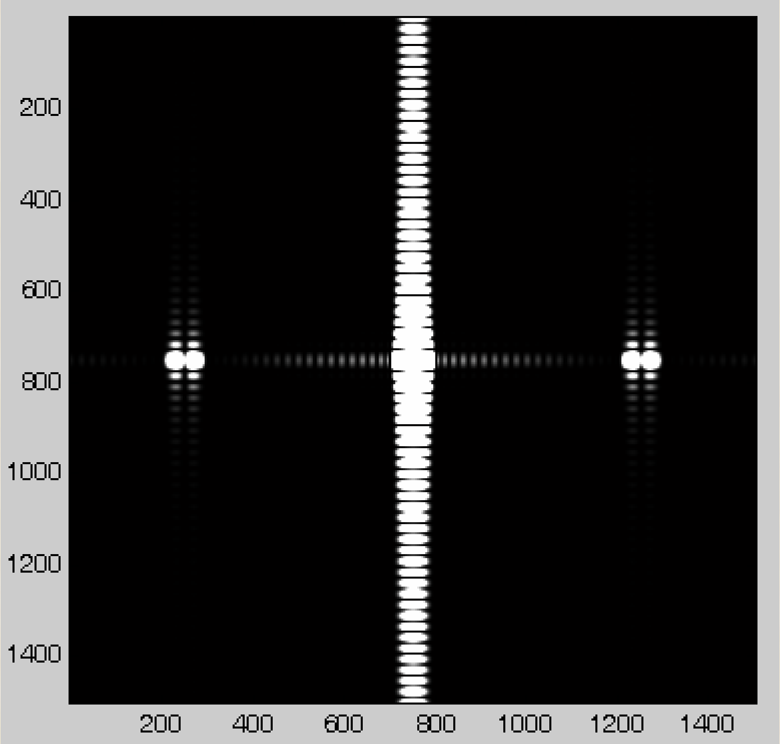


The plot of simulated PSF at the focal plane: 10^{-10} contrast imaging at 2 λ/D is achieved.

Case 2: 21-step transmission filters (throughput=38.0%)

Transmission Pupil:
consists of one transmission filter.

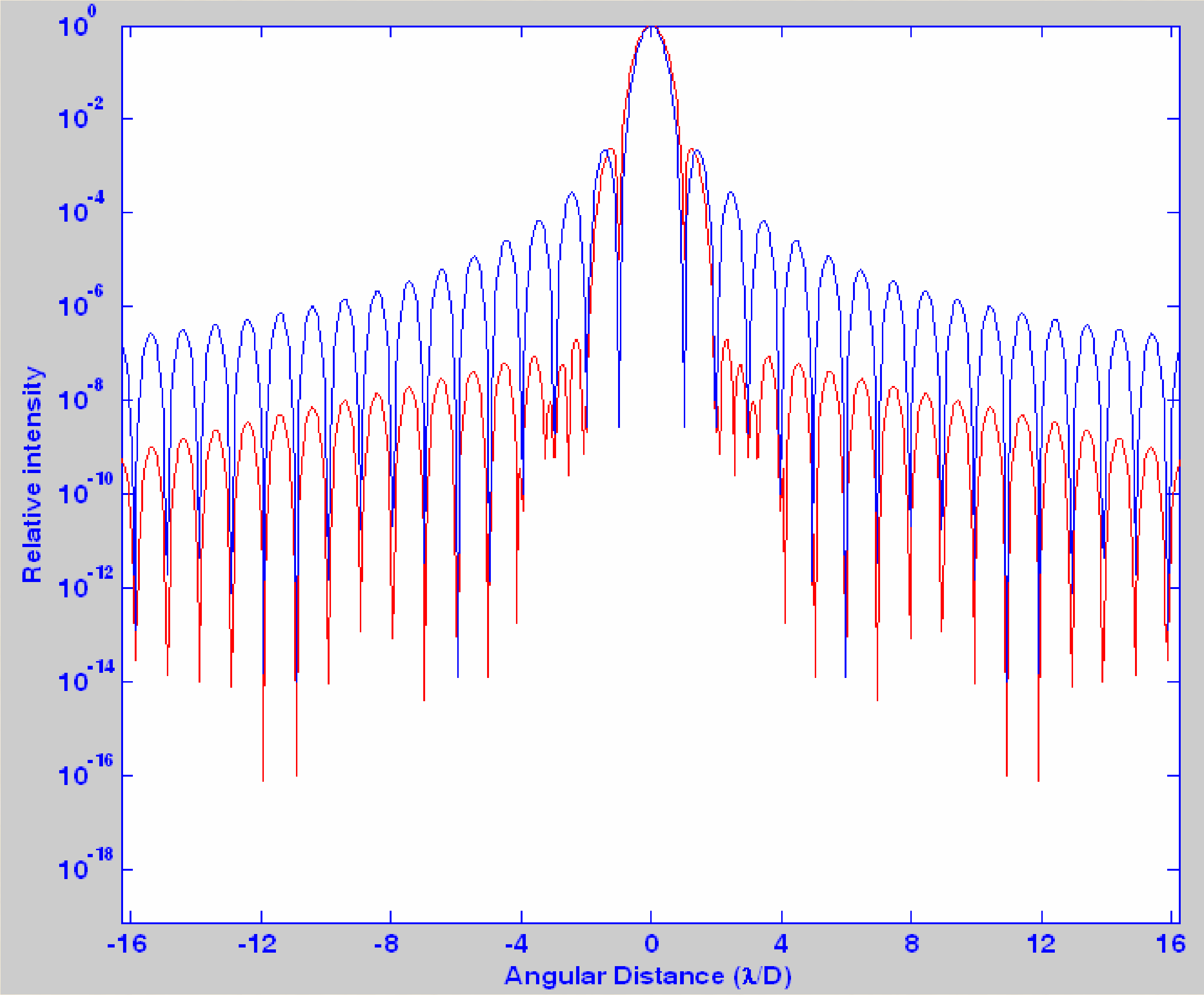




PSF at the focal Image Plane
(One filter)

Case 2: 21-step transmission filters (throughput=38.0%)

Theoretical Performance (One filter)



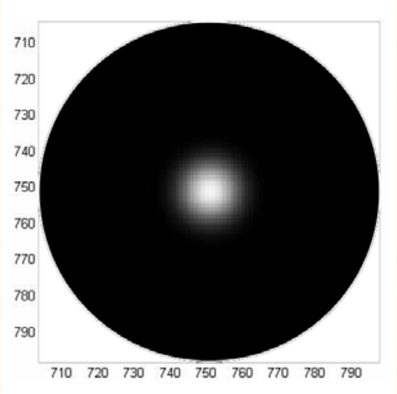
The plot of simulated PSF at the focal plane: 10^{-7} contrast imaging at 2 λ/D is achieved.

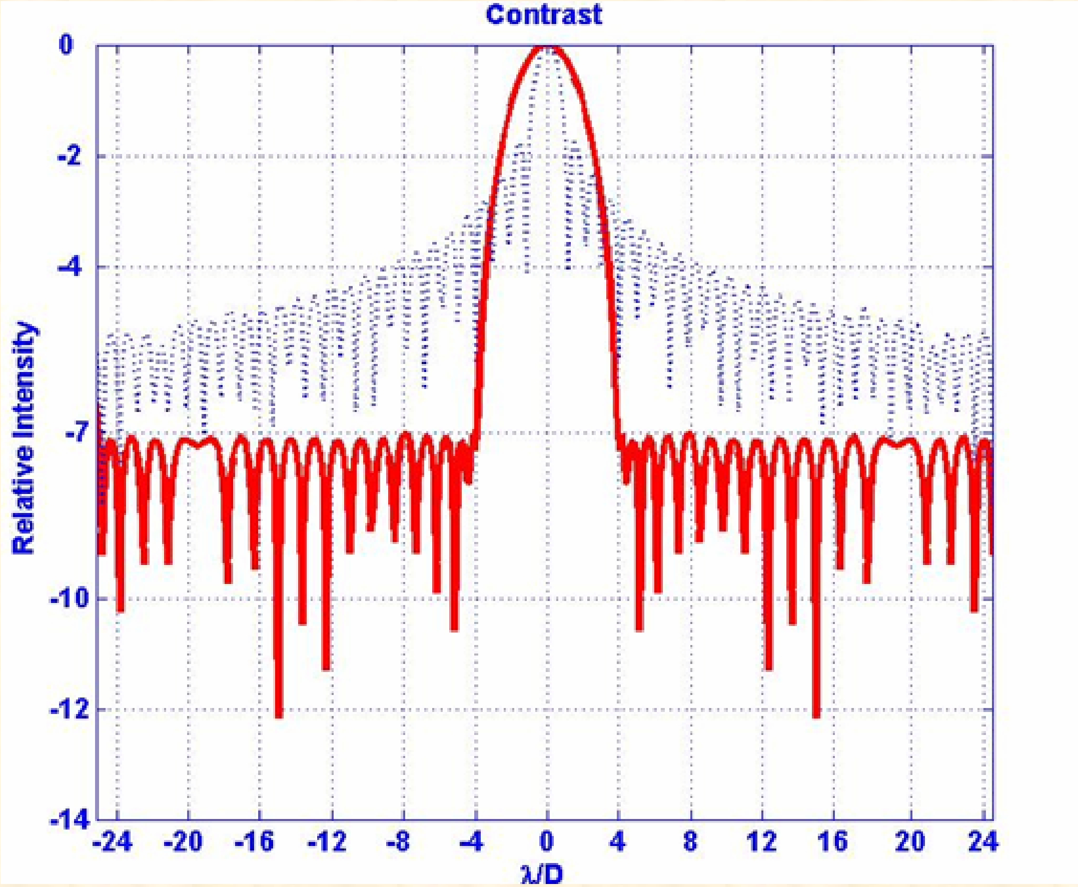
Case 3: 29-circular-step transmission filters (throughput=10%)

Optimized for Circular Pupil

Pupil

PSF





The plot of simulated PSF at the focal plane:

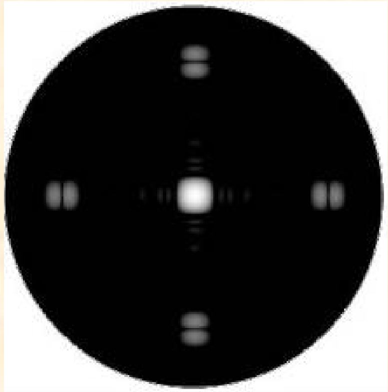
10^{-7} contrast imaging at 4 λ/D is achieved.

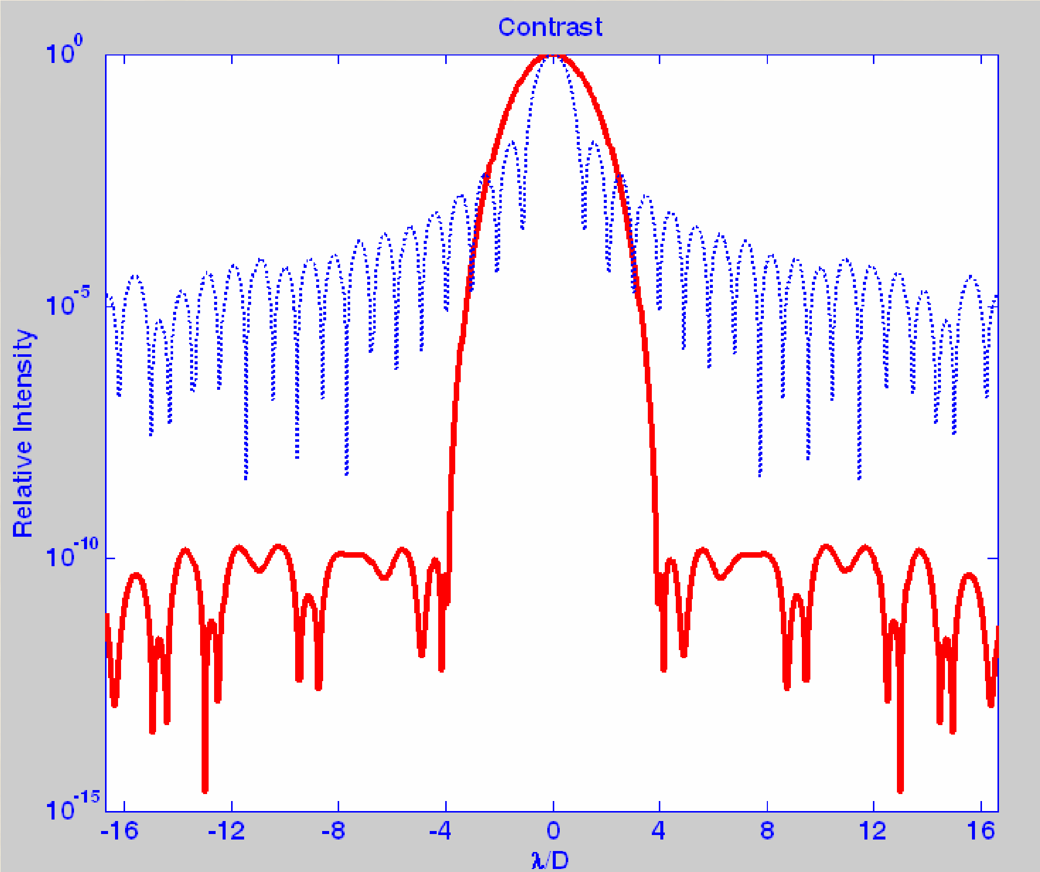
Case 4: 21-circular-step transmission filters (throughput=7%)

Optimized for Circular Pupil

Pupil

PSF





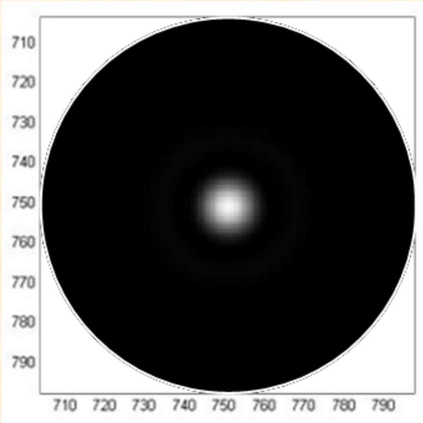
The plot of simulated PSF at the focal plane: 10^{-10} contrast imaging at 4 λ/D is achieved.

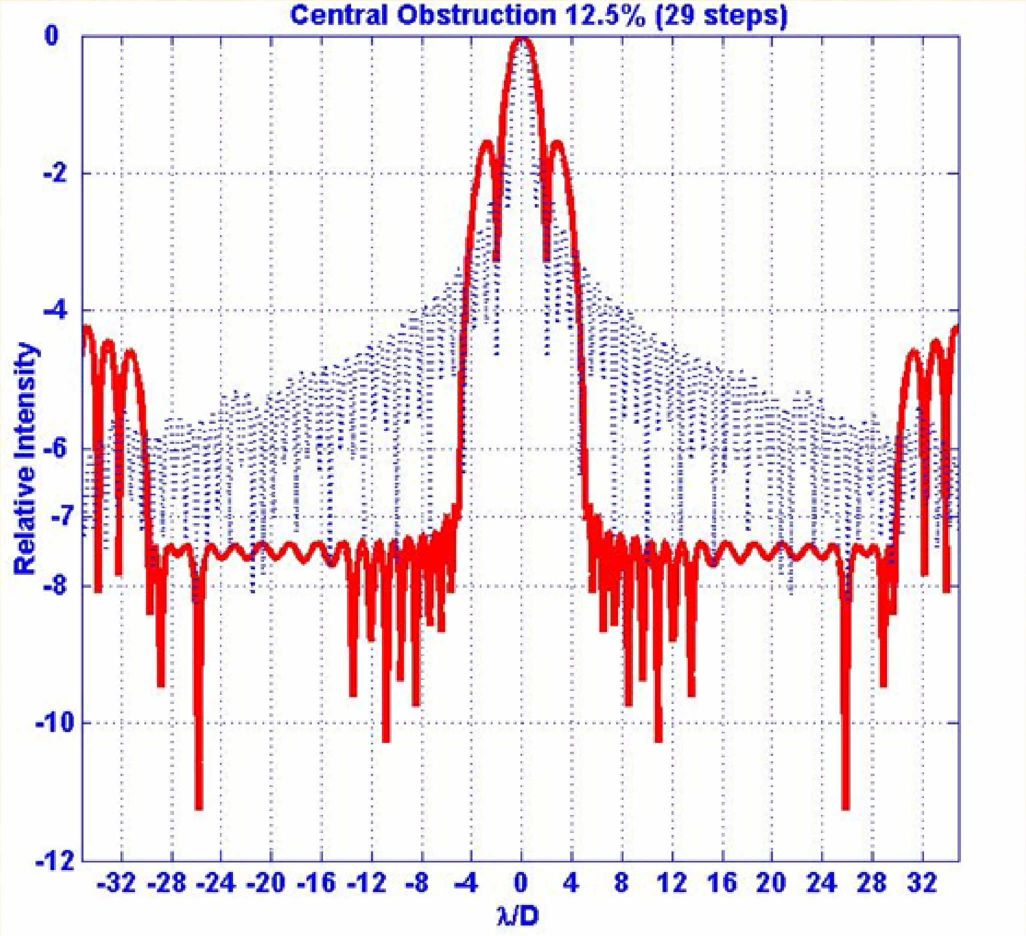
Case 5: 21-circular-step transmission filters (throughput=22%)

Optimized for telescope with central obstruction

Pupil

PSF





The plot of simulated PSF at the focal plane: $10^{-7.5}$ contrast imaging at 4 λ/D is achieved.

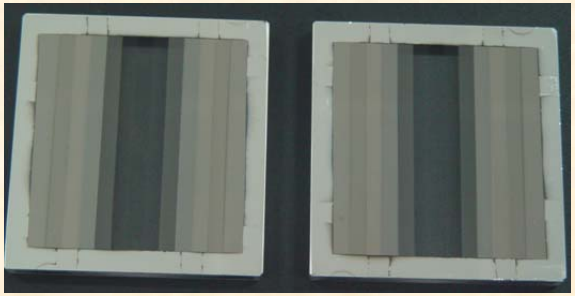
3. Coronagraph Laboratory Test

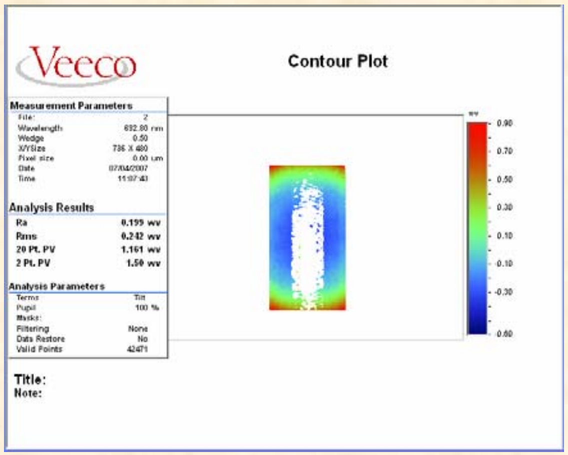
(13-step transmission filter based)

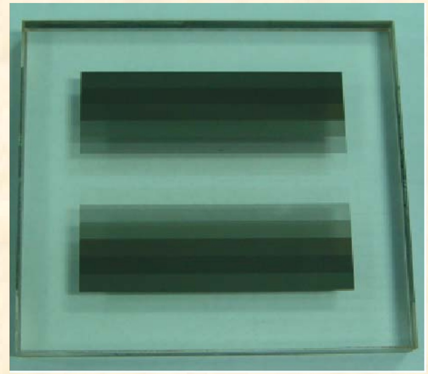
(Dou,Ren,Zhu, et al. 2008,2009 SPIE Proc.)

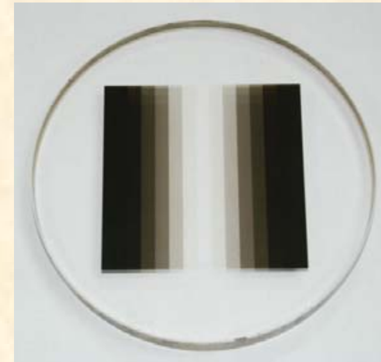
3.1. Coronagraph was setup and tested in Laboratory

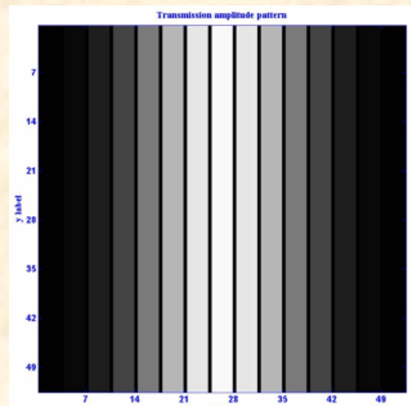
3.2. Several manufactured transmission filters

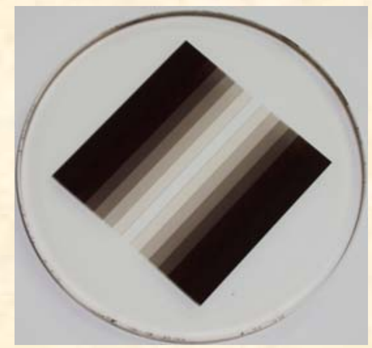












USA:OMEGA OPTICAL

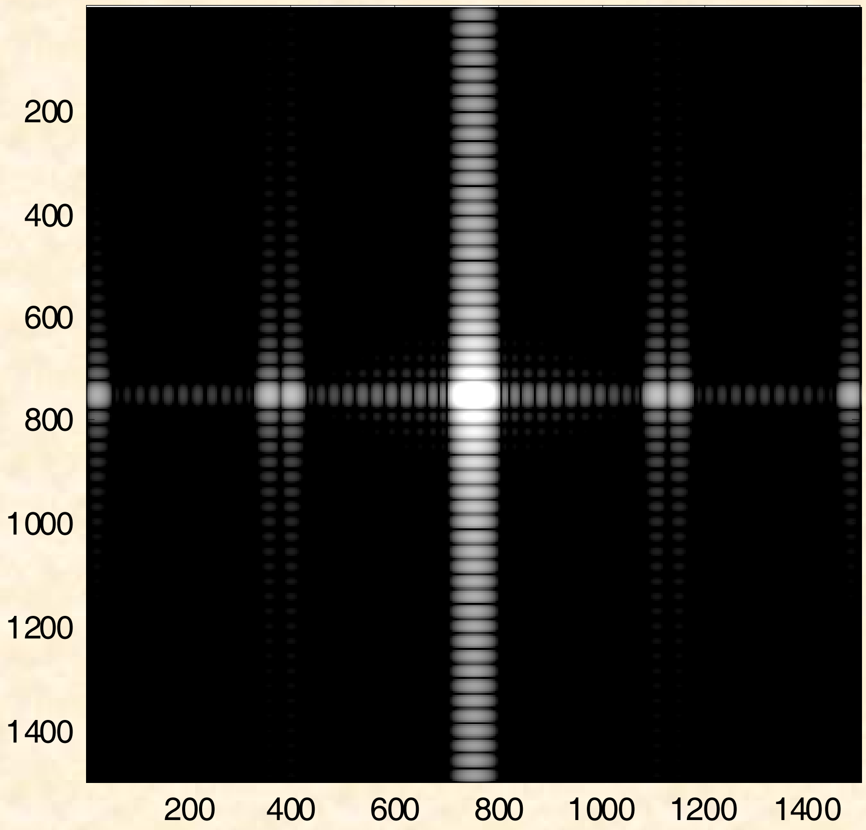
China: Changchun Institute

Table 1. Design Specifications of the stepped filter.

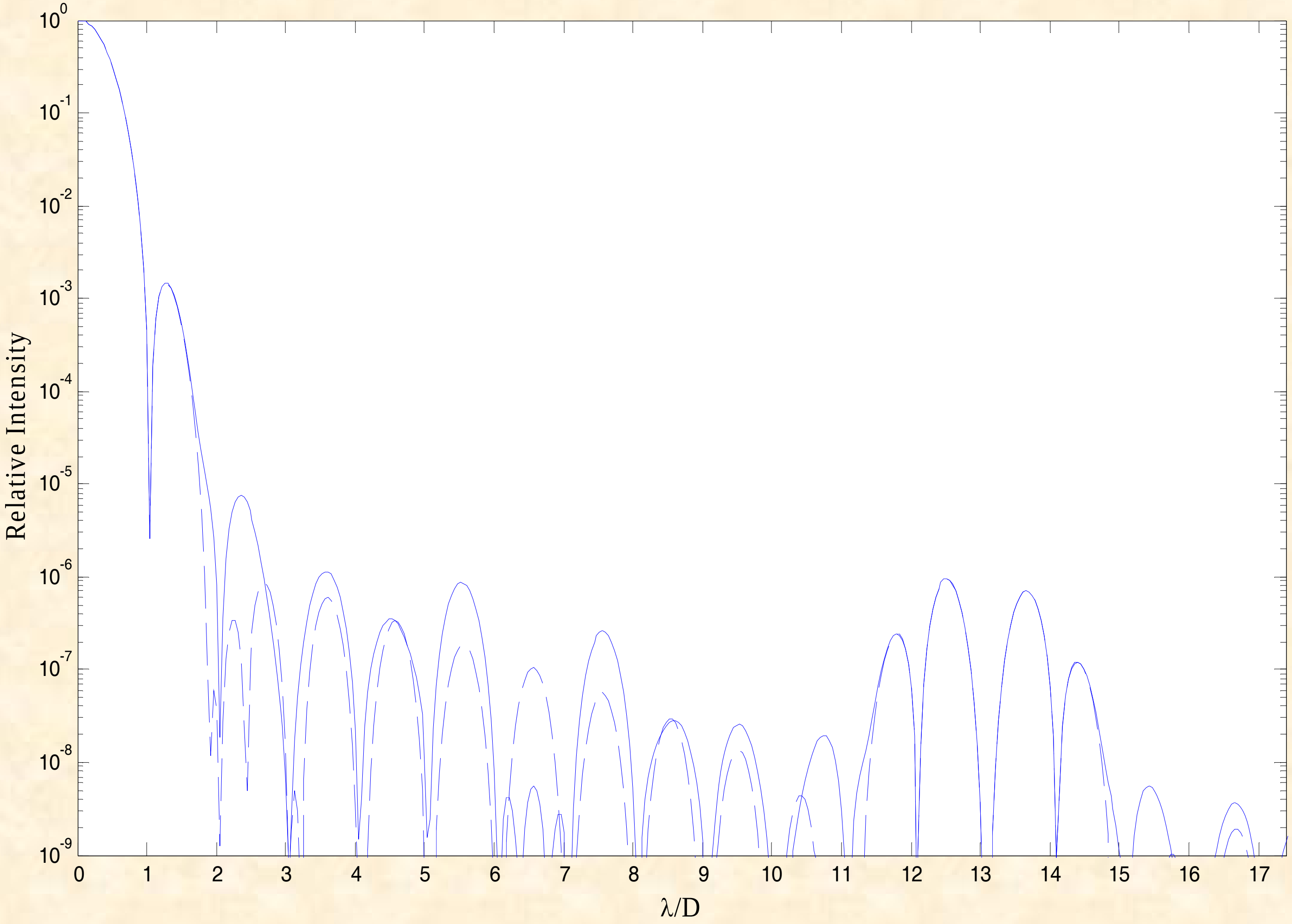
Step number	Contrast	Wavelength	Throughput	Transmission	Size precision
13	10^{-6}~10^{-7} at 2~4 λ/D	0.6328 um	41%	+/- 3 %	20 nm

PSF without Wave-Front Error (One Filter)

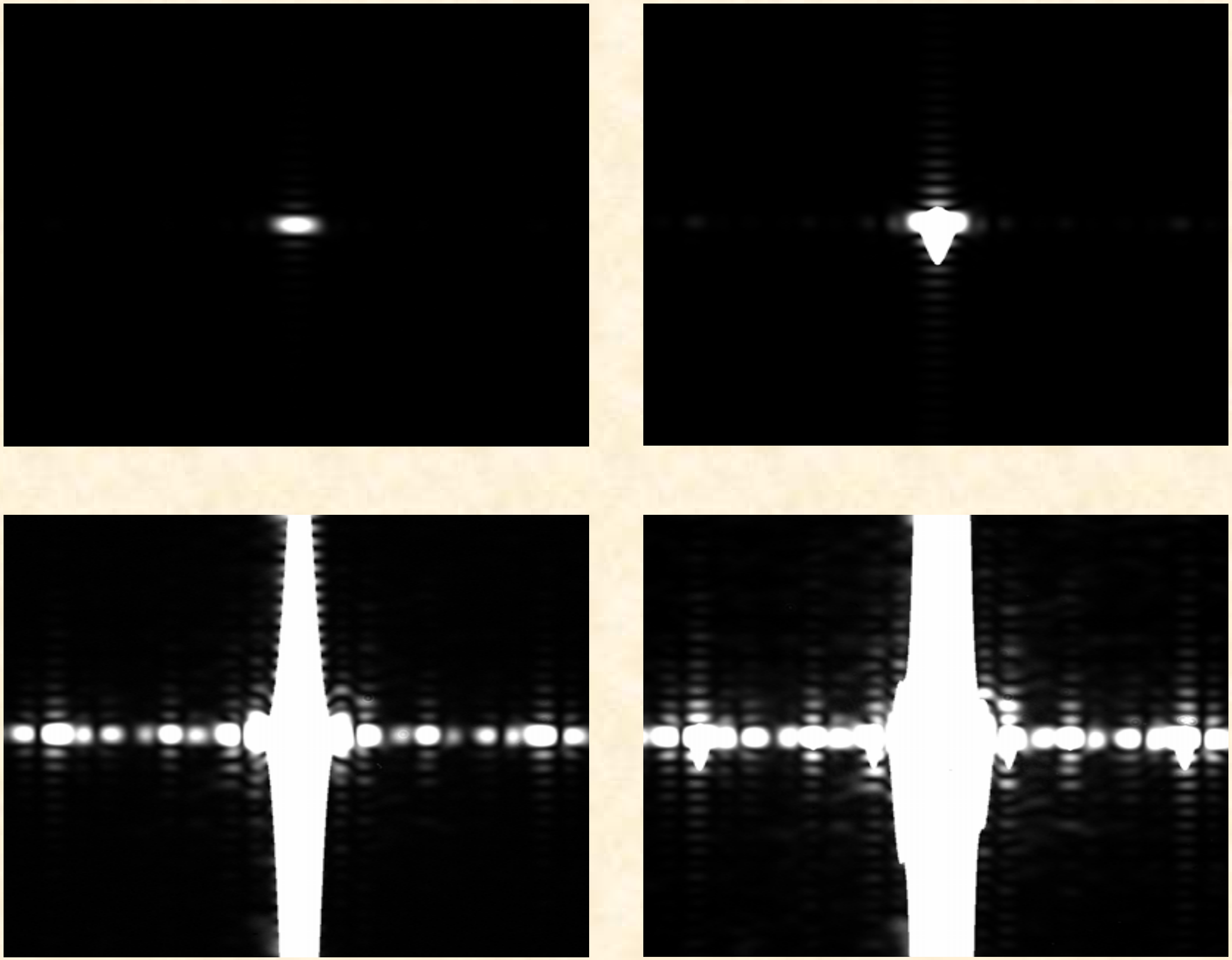
(simulation)



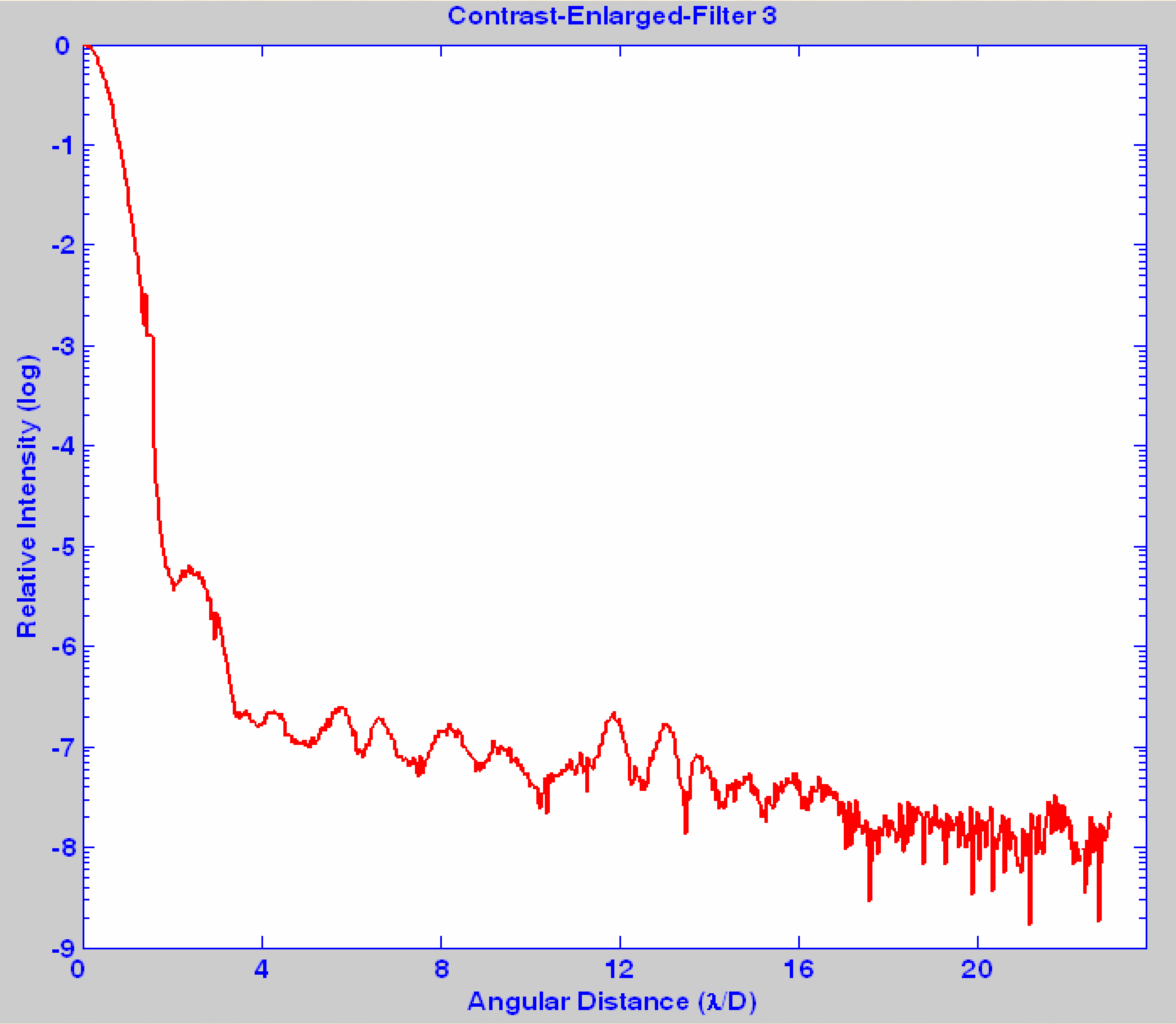
Theoretical PSF with (solid line) and without (dashed line) transmission error.



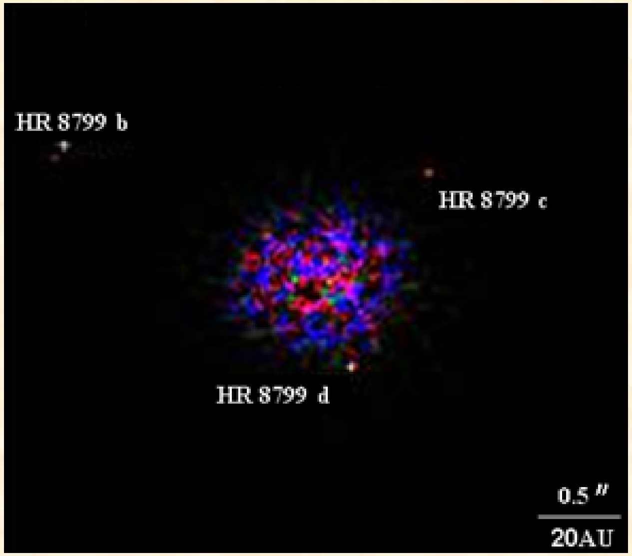
Using one filter 1:   Tested PSF images at different exposure times

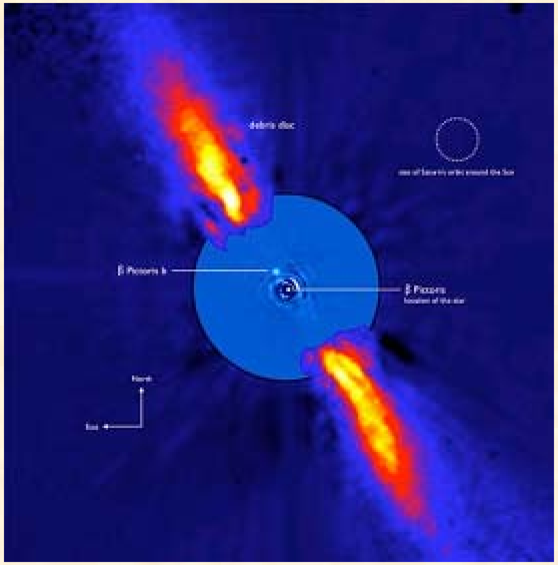


Filter 1: Tested contrast along diagonal directions



4. Ground-based Imaging





Direct imaging of the young giant planets in Infrared Wavelength

Exoplanets discovered by direct imaging method

Using conventional Lyot Coronagraph

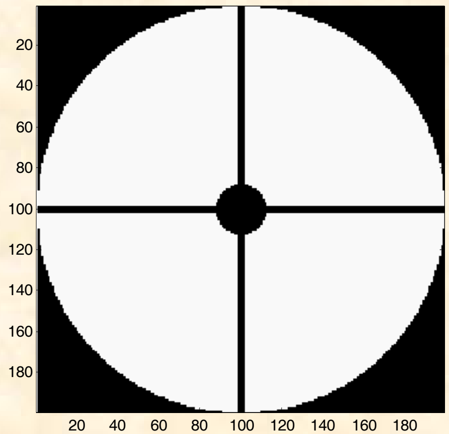
Star I	Distance from Earth	T_{eff} [K]		
β Pictoris	19.1~19.5pc	7950		
Planets	Distance (Angular)	T_{eff} [K]		
β Pic b	8AU(0.4")	1600-1400		
Star II	Distance from Earth	T_{eff} [K]		
HR8799	38~40pc	7505-7305		
Planets	Distance (Angular)	T_{eff} [K]	Contrast	Wavelength
HR8799 b	24AU(0.63")	900-800	$10^{-3.4}$~$10^{-5.7}$	J,H,K (1.25,1.65,2.2 μm)
HR8799 c	38AU(1")	1100-1000	$10^{-2.7}$~$10^{-4.4}$	
HR8799 d	68AU(1.8")	1100-1000	$10^{-2.7}$~$10^{-4.4}$	

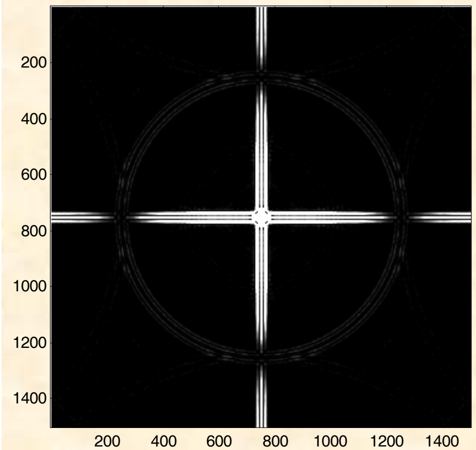
4. Ground-based Imaging

-- Coronagraph for ground-based telescopes

Dou, J. P., Ren, D.Q., Zhu, Y.T., et al., RAA (Submitted)

We are making a step-transmission filter that can be used with a ground-based telescope with central obstruction and spider structure.





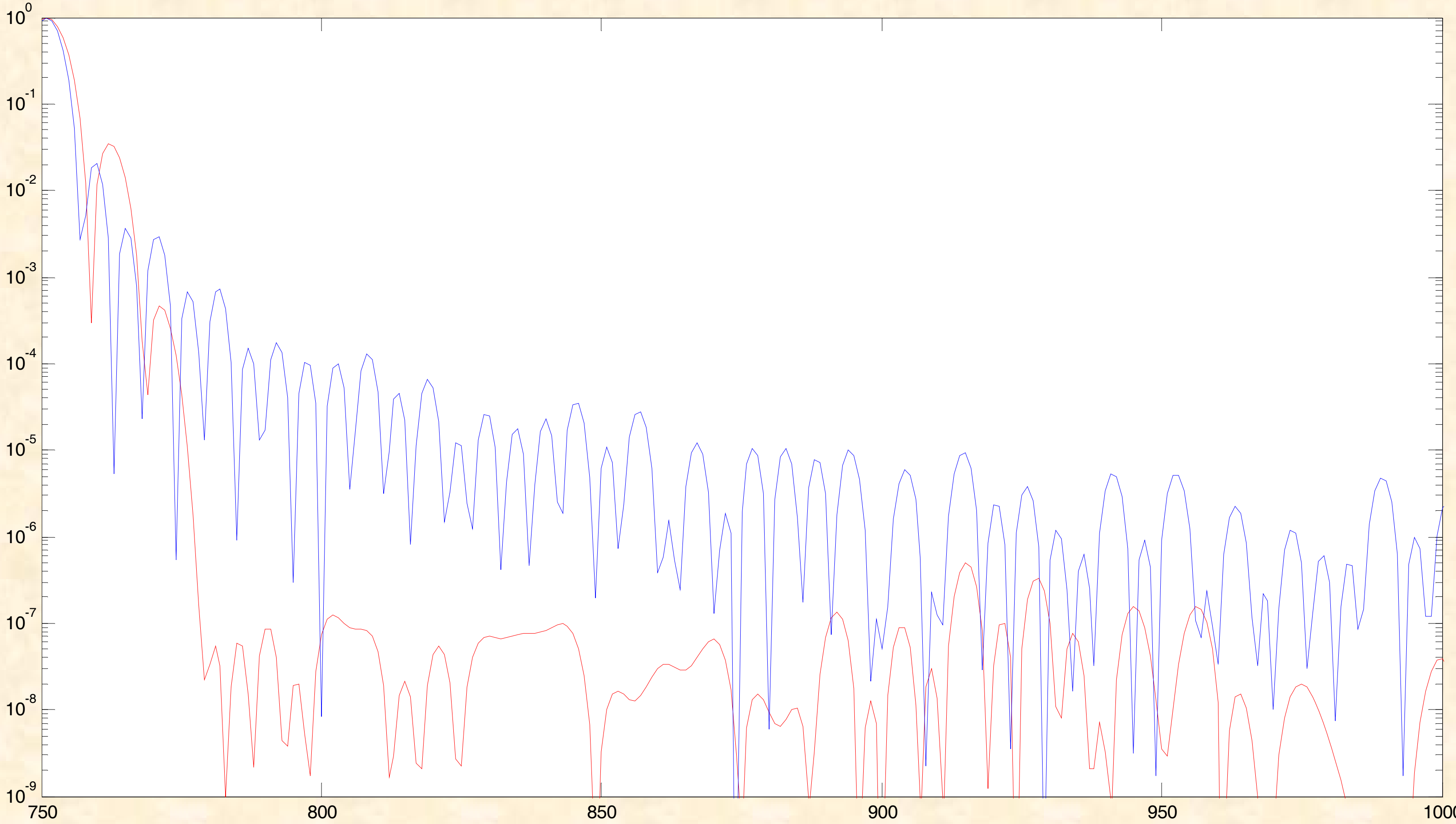
Walk out from the laboratory!

On the way now…

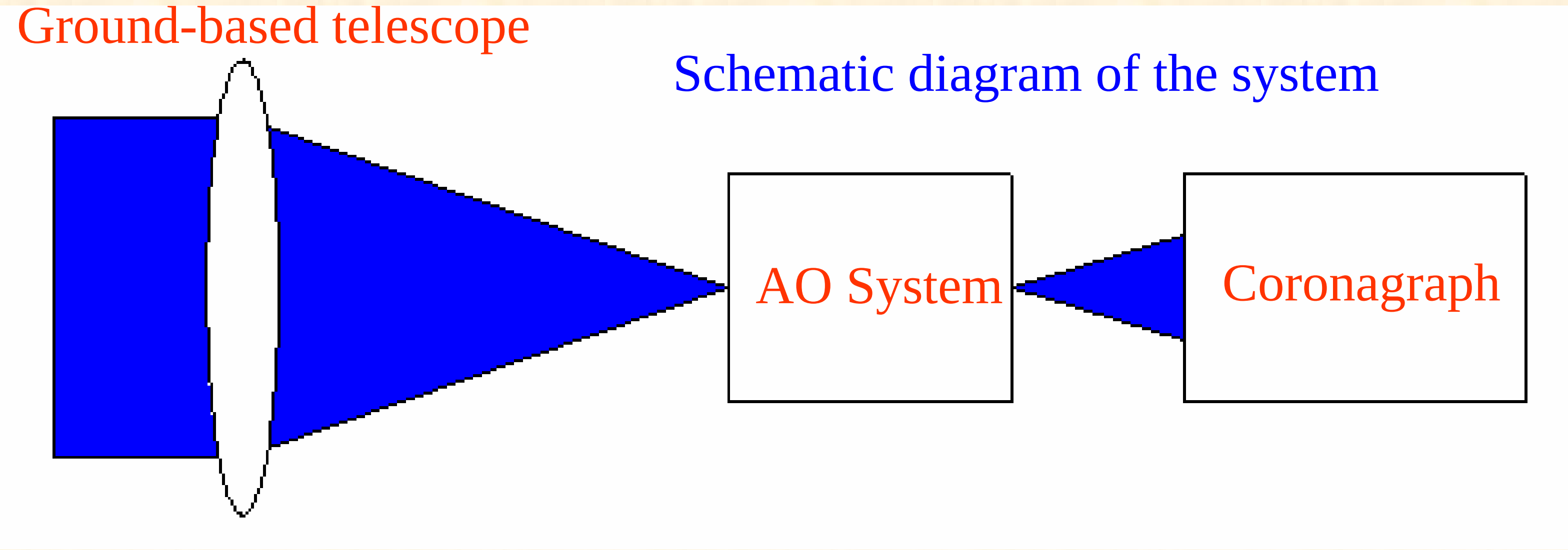
4. Ground-based Imaging

-- Coronagraph for ground-based telescopes

Contrast in the order of 10^{-7} should be achieved at $3\sim5\lambda/D$ with the step-transmission filter for a ground-based telescope.



Principle of Operation



Thirsty for Large Telescope!!

Possible applications

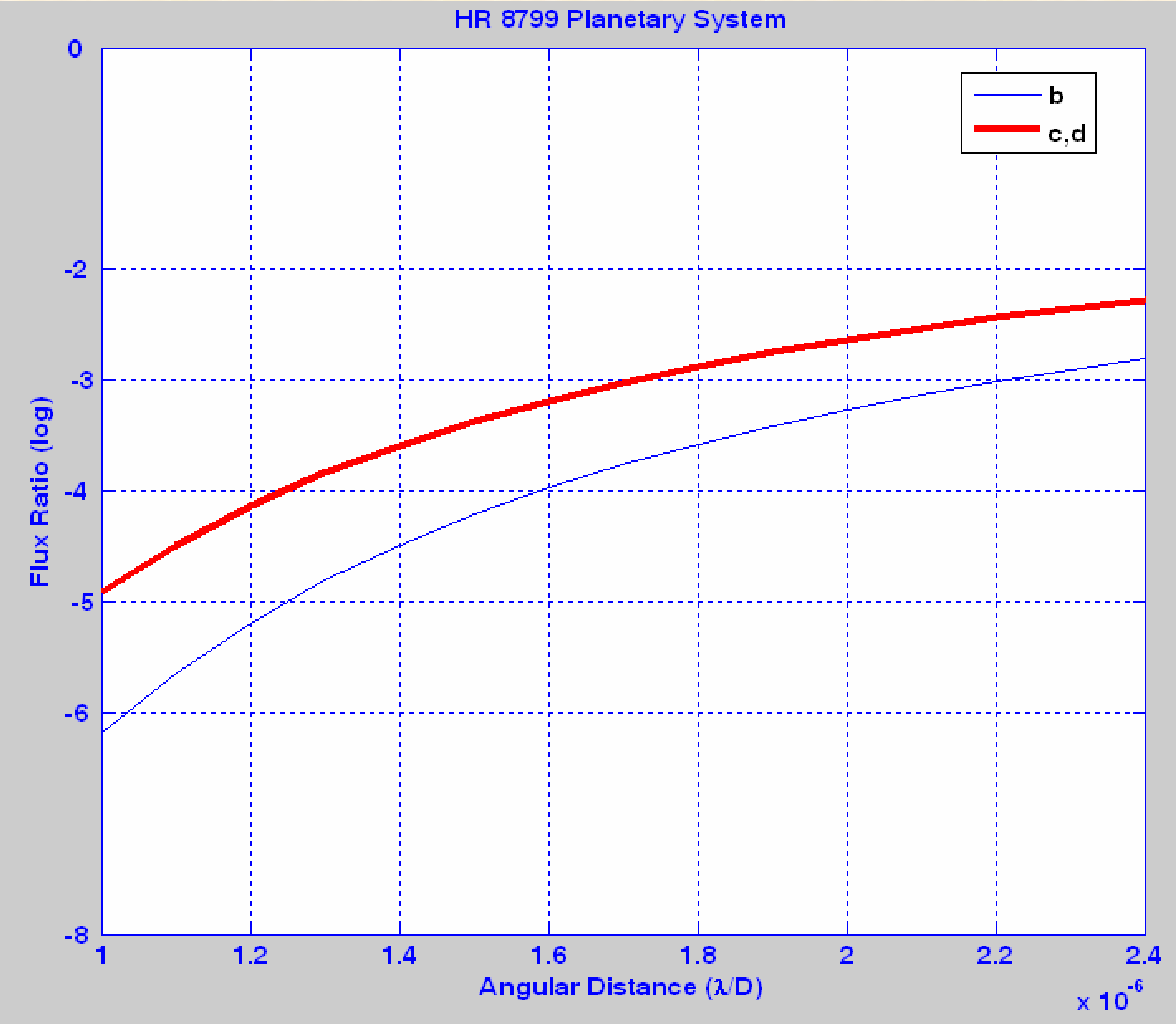
The coronagraph will be best used with a large ground-based telescope equipped with state-of-the-art AO system:

- Subaru 8-meter telescope
- Keck 10-meter Telescope
- Other 4~6 meter class telescopes

Some potential planets candidates:

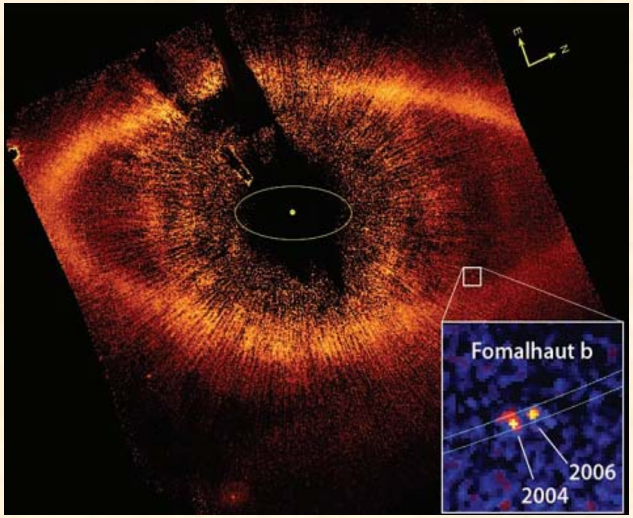
- a) direct image of the extra-solar planets that have been detected through traditional coronagraph imaging;
- b) direct image the unconfirmed extra-solar planet candidates;
- c) direct image some new planets with most favorable contrast of their primary stars: direct image regions around some of the young M stars.

Wavelength



HR 8799 Planetary System
Flux Ratio (log)
Angular Distance (λ/D)
x 10^-6
b
c,d
0
-2
-3
-4
-5
-6
-8
1
1.2
1.4
1.6
1.8
2
2.2
2.4

5 Space-based Imaging



Direct imaging of the earth-like planets

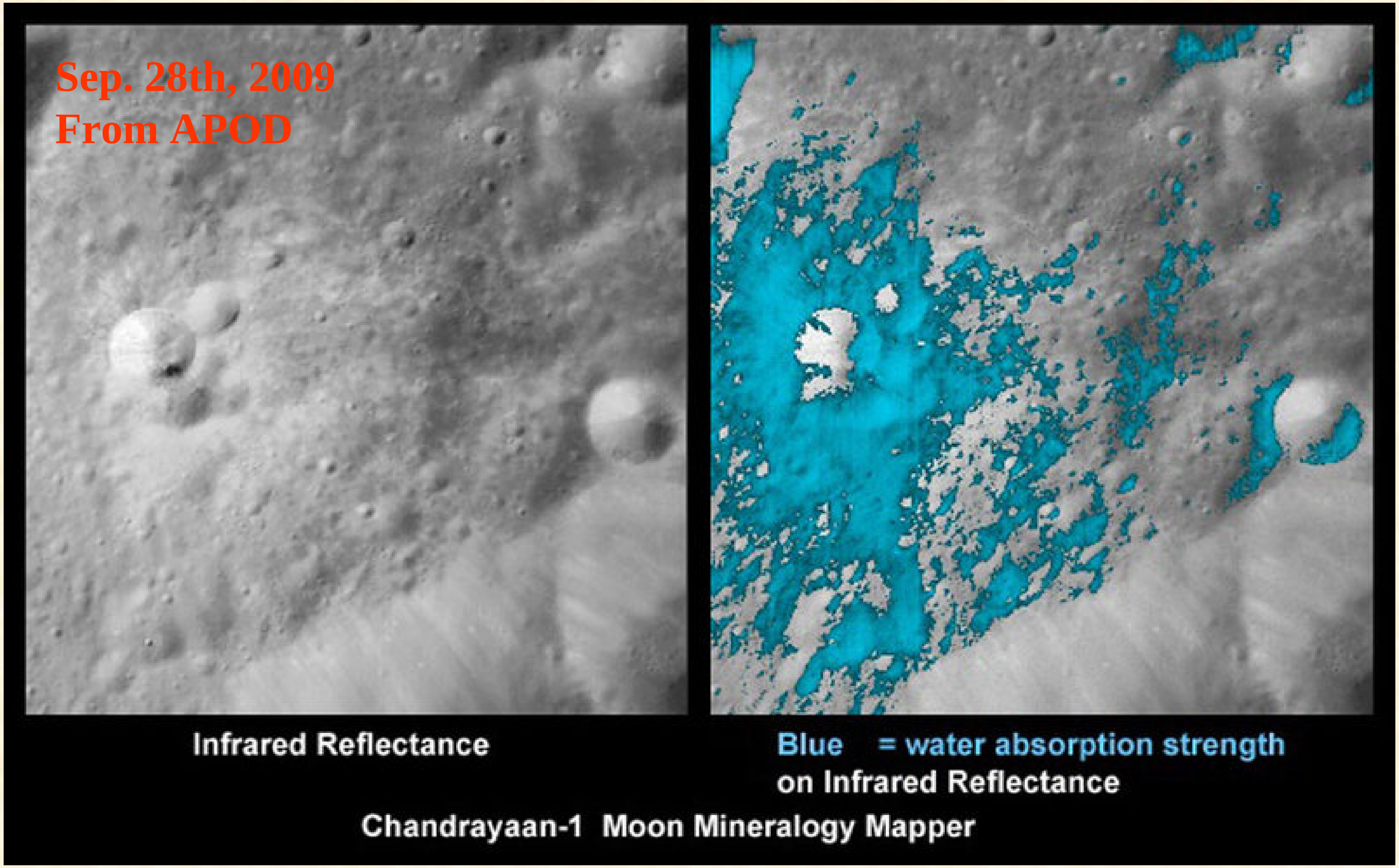
HST

. Telescope: off-axis &4-m class at least

. Contras: 10^{-9}~10^{-10}

. Wavelength: Visible

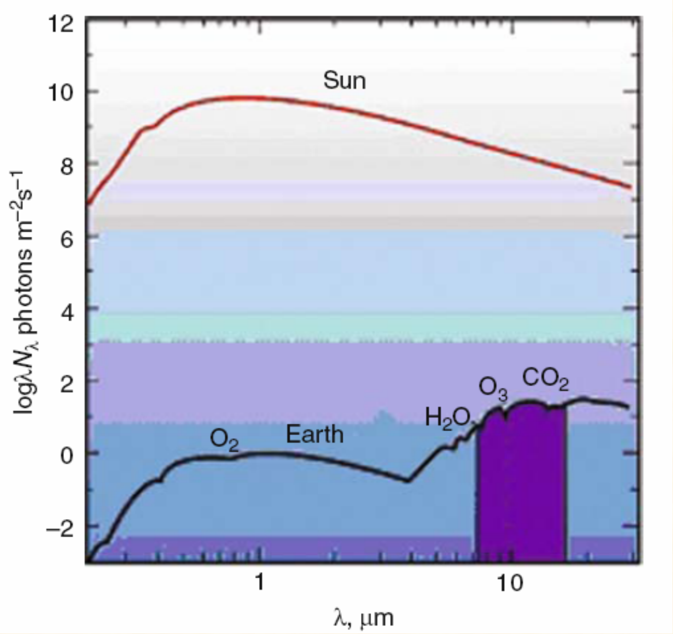
5 Space-based Imaging

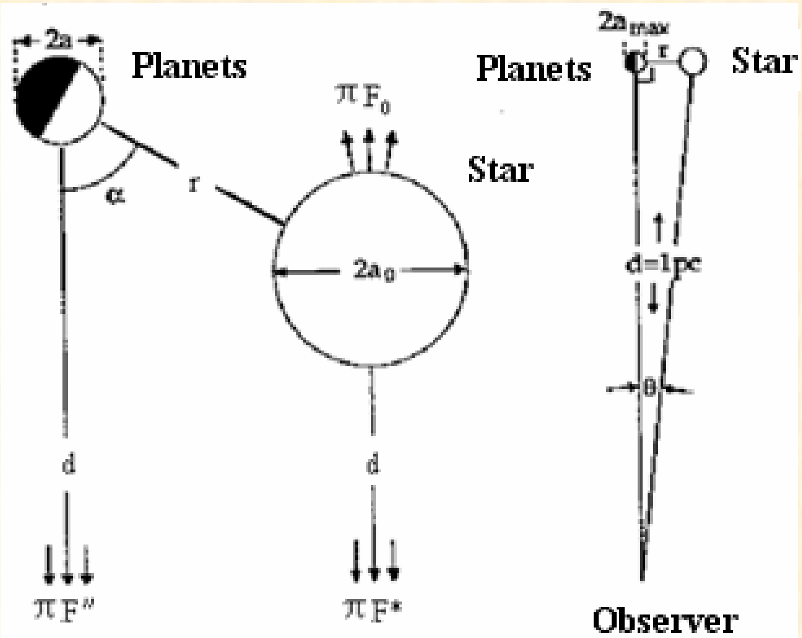


Water has been discovered on the surface of the Moon!

5 Space-based Imaging

$$\frac{\pi F''}{\pi F^*}|\max = (0.4)(0.25)(\frac{8.3\times10^4}{1.49\times10^8})\frac{1}{d(PC)^2}\frac{1}{\theta('')^2} = \frac{3.1\times10^{-8}}{d(PC)^2\theta('')^2}$$





Brown, R. A. & Burrows, C.J. , ICARUS, 1990(87):484-497

5 Space-based Imaging

Coronagraph with transmission apodization plus induced phase

- Using the Deformable Mirror (DM) of an adaptive optics to change the phase according to our algorithm.
- To provide an extra contrast gain of 10^{-3}.
- Combining with the filter (10^{-6}~10^{-7}), our coronagraph with filter and DM will be able to achieve 10^{-9}~10^{-10} contrast.

Dou, J., Ren, D., Zhu, Y. et al., Sci China Ser G-Phys, 2009,52 (8) :1284-1288

Mathematics for numerical optimization

The amplitude of the electric field of the light wave at the pupil is

$$E(u,v) = A(u,v)e^{i\phi},$$

We can a DM to modify the phase ϕ to achieve an extra gain for the contrast.

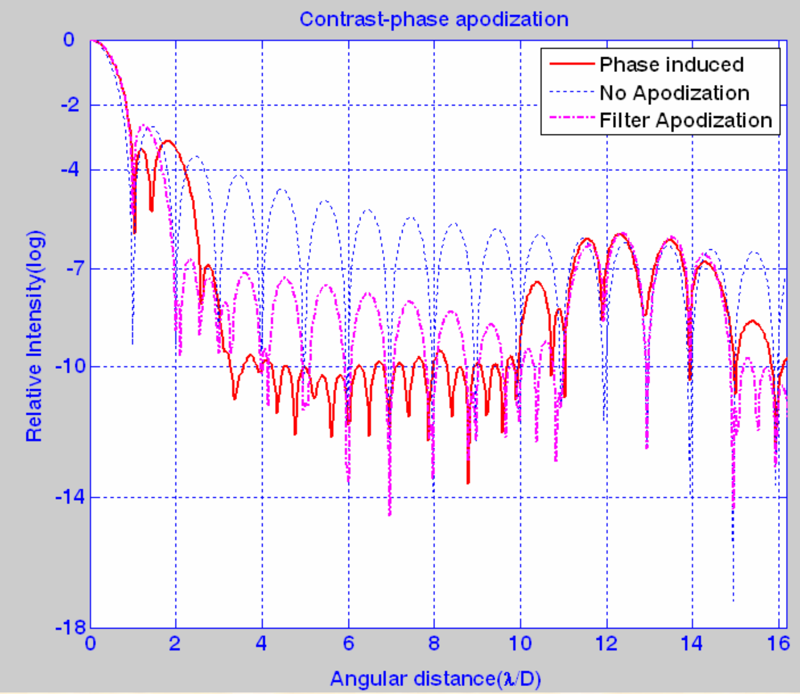
The optimum solution for phase ϕ can be found from the numerical optimization,

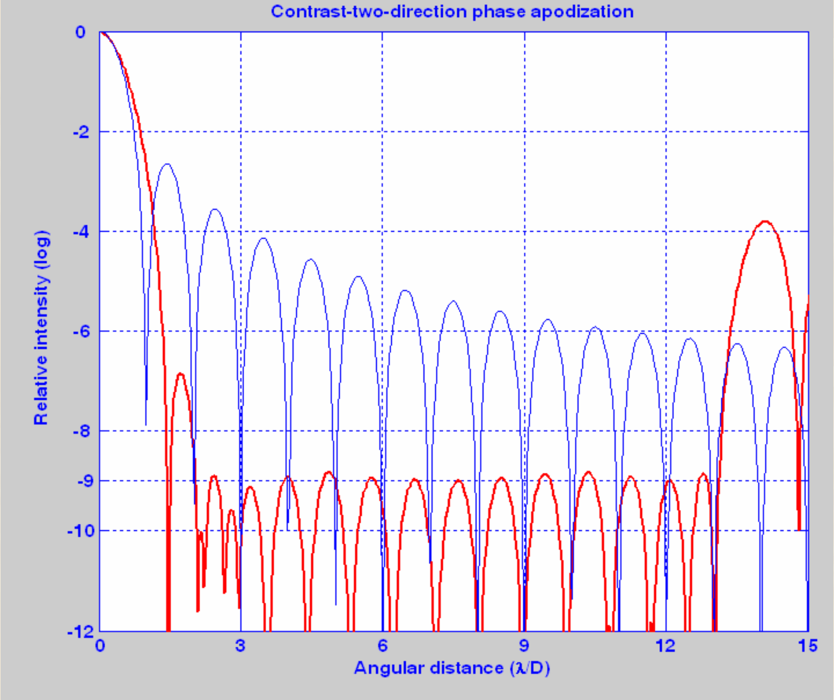
$$Min\{ \ \sum | \ (I(x,y) - I_{est} \ | \ \},$$ subject to $I(x,y) \in$ discovery area

$$where\ I(x,y) = | \ \iint_{-\infty}^{+\infty} E(u,v)e^{i(xu+yv)}dudv \ |^2 = | \ \vec{F}[\ E(u,v) \ ] \ |^2,$$

$I_{est} = 10^{-7}$, or 10^{-10} is the optimzed contrast.

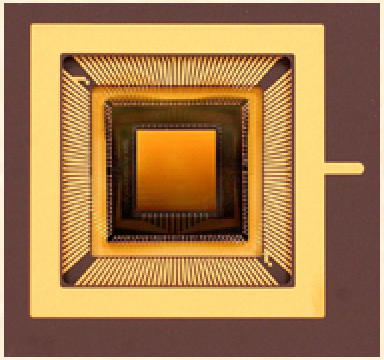
Coronagraph with DM correction:
Some numerical simulation results





Deformable Mirror

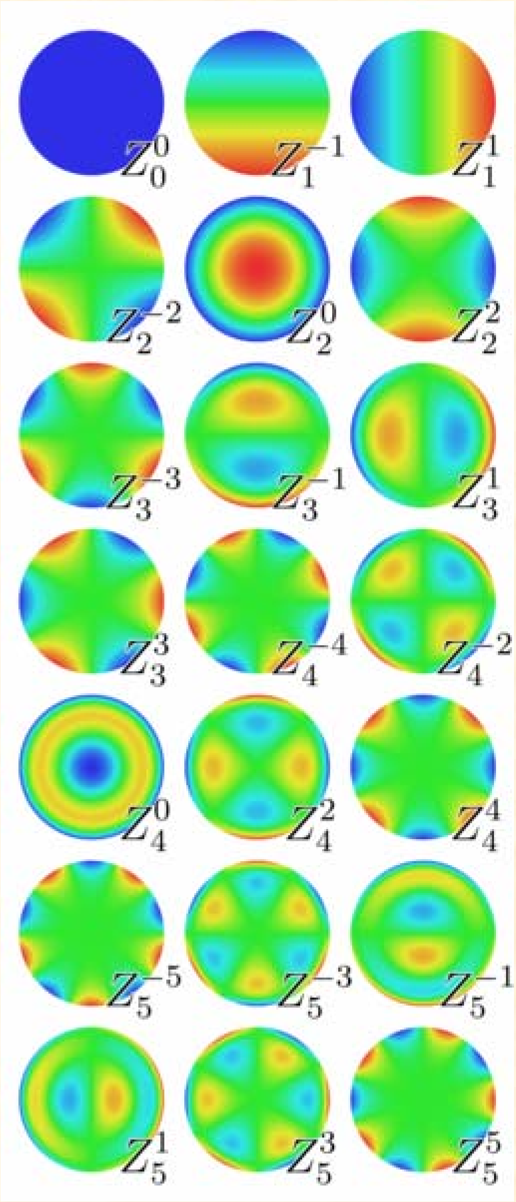
- Deformable Mirror with 12x12 actuators was purchased from Boston Micromachines under testing.
- First light will be available late this year.



Hartmann Wave-front Sensor

- Hartmann wave-front sensor.
- Wave-front is reconstructed by Zernike Polynomials:

$$\phi = \sum_{k=1}^{K} a_k Z_k(x, y)$$



Wave-front reconstruction approach

$$s = \begin{pmatrix} \Delta x = \frac{\partial \phi}{\partial x}\Big|_1 \\ \Delta y = \frac{\partial \phi}{\partial y}\Big|_1 \\ \vdots \\ \Delta x = \frac{\partial \phi}{\partial x}\Big|_M \\ \Delta y = \frac{\partial \phi}{\partial y}\Big|_M \end{pmatrix} \qquad a = \begin{pmatrix} a_1 \\ a_1 \\ \vdots \\ a_k \end{pmatrix}$$

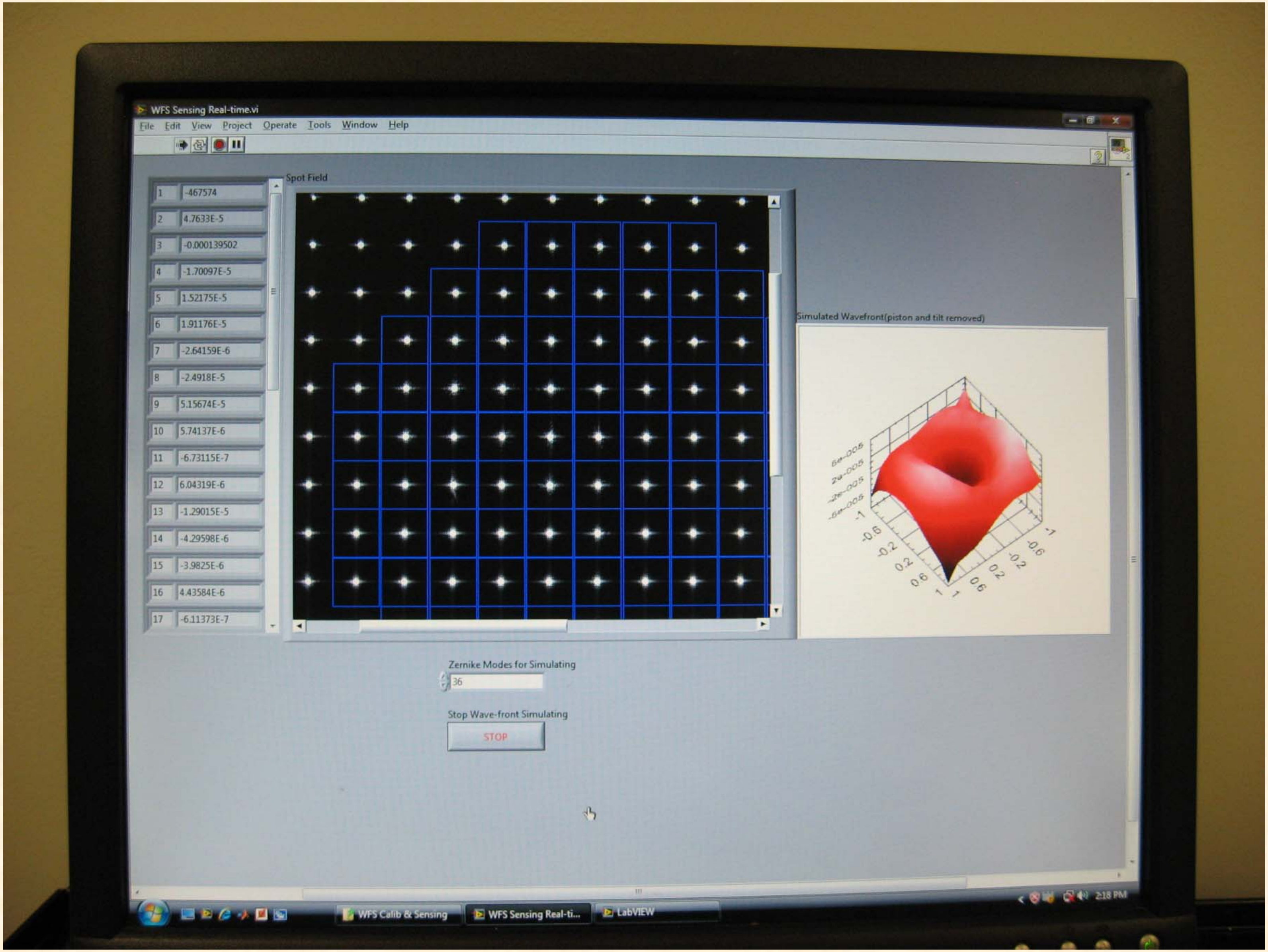
$$[B] = \begin{pmatrix} \frac{\partial Z(x,y)_1}{\partial x}\Big|_1 & \cdots & \frac{\partial Z(x,y)_k}{\partial x}\Big|_1 \\ \frac{\partial Z(x,y)_1}{\partial y}\Big|_1 & \cdots & \frac{\partial Z(x,y)_k}{\partial y}\Big|_1 \\ \vdots & & \\ \frac{\partial Z(x,y)_1}{\partial x}\Big|_M & \cdots & \frac{\partial Z(x,y)_k}{\partial x}\Big|_M \\ \frac{\partial Z(x,y)_1}{\partial y}\Big|_M & \cdots & \frac{\partial Z(x,y)_k}{\partial y}\Big|_M \end{pmatrix}$$

The Wave-front Reconstruction Matrix is

$$s = [B]a$$

a must be found by using Singular Value decomposition (SVD) bscause of the ill-posed data set.

Wave-Front Sensor Graphic Interface



6. Conclusions & Future Development

- Our coronagraph achieved 10^{-6} contrast that is one of the best coronagrapgic results in the laboratories (Dou et al. 2008 SPIE 7010, Thomas et al. 2008 SPIE 7015, Enya et al. 2007, Kasdin et al. 2004).

- The $10^{-6} \sim 10^{-7}$ contrast will be used for the direct imaging of Jupiter-size planets, on a ground-based telescope.

- Combined with a DM, the coronagraph is the patentability to achieve a contrast 10^{-10}.

- The 10^{-10} contrast will be able used for the direct imaging of Earth-like planets, on a space telescope.

6. Conclusions & Future Development

- Speckle-removing Technique
- Differential Imaging Technique
- Interferometric Nulling Technique

Thanks!

And any questions?