Design and verification of external occulters for direct imaging of extrasolar planets

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JPL Postdoc Seminar Series
February 10, 2011

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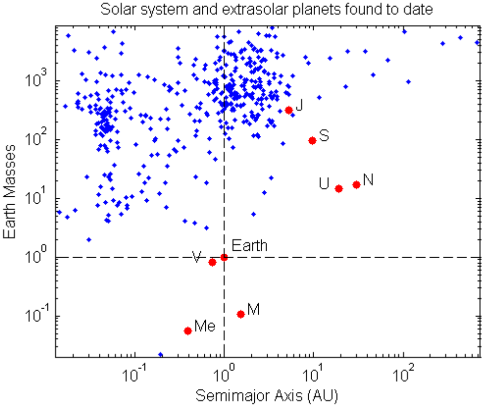
Finding planets

1995: 51 Pegasi b is the first planet found around a Sun-like star (Mayor and Queloz 1995).

Since then: over 500 planets found and counting, mostly hot, close gas giants



Courtesy of D. Savransky

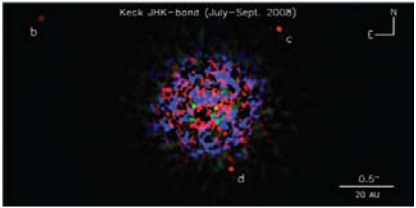
We'd like to start finding objects similar to Earth.

Planet-finding methods

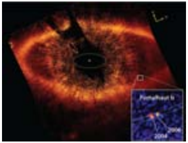
The problem: How do we find and characterize Earth-size planets?

Many approaches to find planets:

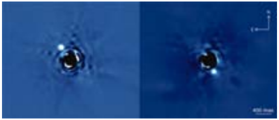
- Radial velocity
- Transits
- Astrometry
- Microlensing
- Pulsar timing
- Direct imaging (in particular, from space)



HR8799 (Marois *et al.* 2008)



Fomalhaut (Kalas *et al.* 2008)



β Pictoris (Lagrange *et al.* 2010)

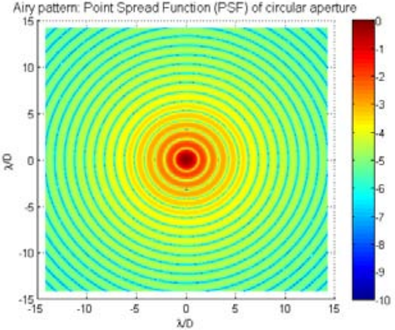
Going to space

Some advantages in space over ground-based telescopes, even very large ones!

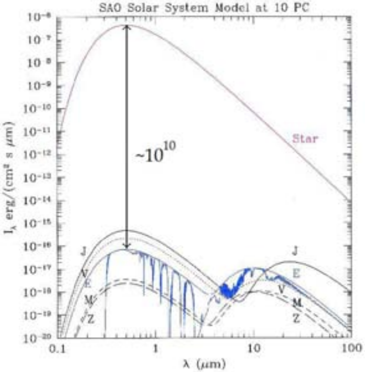
- No atmospheric aberrations (Reduced adaptive optics requirements.)
- No atmospheric absorption (In particular, can see UV.)

There are still two problems to overcome, though:

Diffraction:



Contrast:

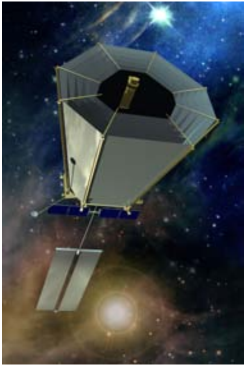


(Des Marais *et al.* 2002)

How to do direct imaging from space?

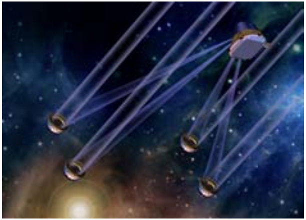
There are a few approaches:

coronagraphs,



tpf.jpl.nasa.gov

interferometers,



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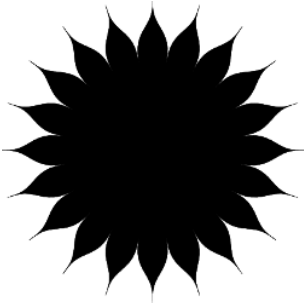
and occulters.



Kasdin *et al.* 2009

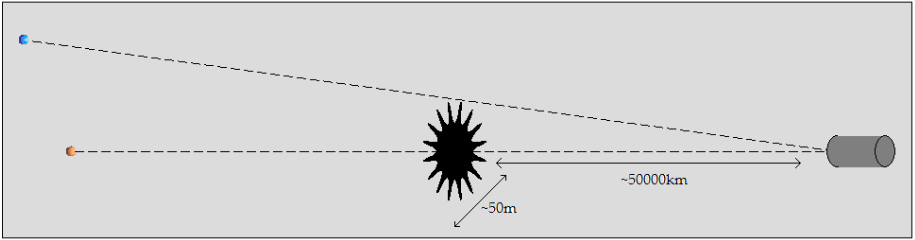
and I'll focus on occulters for this talk.

Occulter design

What is an occulter?

Occulters

An occulter is an optical element which is placed in front of the telescope to block most of the light from a star before it reaches the optics inside, without blocking the planet.



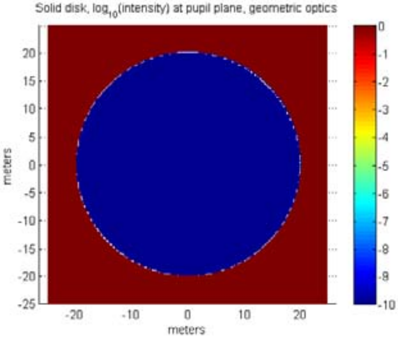
In our case, we use two spacecraft flying in formation:

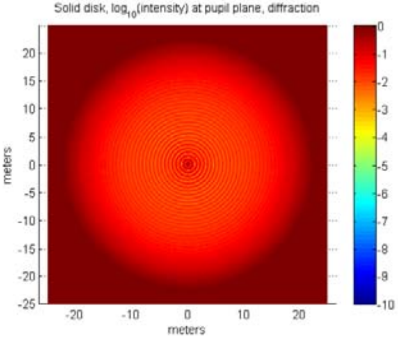
- First has its edge shaped to cancel the starlight
- Second is the telescope which images the star and planet

Why not a disk for planets?

Problem with a simple disk: while geometric optics predicts complete suppression, wave optics predicts diffraction around the edges.

1. On-axis, creates Poisson's spot in the center of the shadow, where the intensity is not attenuated at all
2. Off-axis, full diffraction calculation shows we can only suppress the starlight by $\sim 10^3$





Designing an occulter (I)

Following (Vanderbei, Cady, and Kasdin 2007), we start by thinking about Fresnel propagation from a plane wave incident on an apodized aperture with circular symmetry :

If the apodization is given by a function $A(r)$, then after a distance z, the electric field is:

$$E_{\mathrm{ap}}(\rho) = E_0 e^{ikz} \left(\frac{2\pi}{i\lambda z} \int_0^R e^{\frac{\pi i}{\lambda z}(r^2+\rho^2)} J_0\left(\frac{2\pi r \rho}{\lambda z}\right) A(r) r \, \mathrm{d}r \right)$$

Designing an occulter (II)

An apodized occulter is the complement of this aperture:

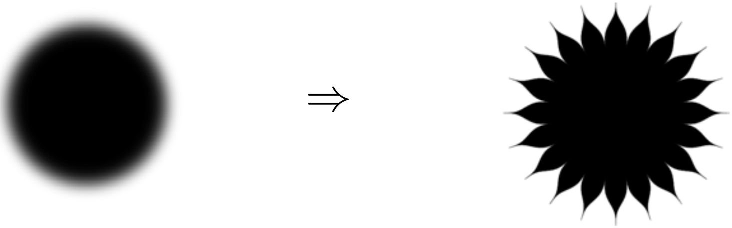
$\Rightarrow$

We can write the equation for this using Babinet's Principle:

$$
\begin{aligned}
E_{\mathrm{occ}}(\rho) &= E_0 e^{ikz}\left(1 - \frac{2\pi}{i\lambda z}\int_0^R e^{\frac{\pi i}{\lambda z}(r^2+\rho^2)} J_0\left(\frac{2\pi r\rho}{\lambda z}\right) A(r) r \,\mathrm{d}r\right) \\
&= E_0 e^{ikz} - E_{\mathrm{ap}}(\rho)
\end{aligned}
$$

Designing an occulter (III)

Can't build an apodized occulter from real materials, so we convert it to a binary occulter with N petals:



Choose petal width so electric field mostly unchanged for small ρ:

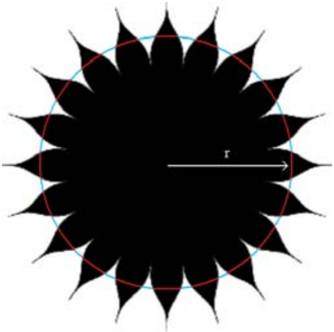
$$E_{\rm bin}(\rho,\phi) = E_{\rm occ}(\rho) - E_0 e^{ikz} \sum_{j=1}^{\infty} \frac{4\pi(-1)^j}{i\lambda z} \cos\left[jN(\phi - \pi/2)\right]$$

$$\times \int_0^R e^{\frac{\pi i}{\lambda z}(r^2+\rho^2)} J_{jN}\left(\frac{2\pi r\rho}{\lambda z}\right) \frac{\sin\left(j\pi A(r)\right)}{j\pi} r\,\mathrm{d}r$$

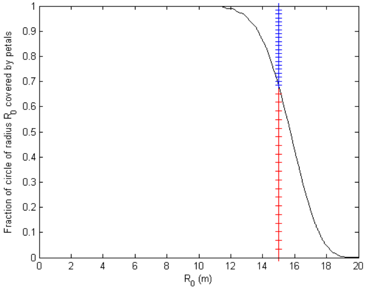
Designing an occulter (IV)

How do we choose the width of the petals?

1. For profile $A(r)$, we design the petals so that a circle of radius r has a fraction of the circle equal to $A(r)$ blocked by a petal
2. We repeat the petals N times to place the scattered light outside the aperture



$\Rightarrow$



Designing an occulter (V)

Lastly, need to choose $A(r)$ and N. We choose $A(r)$ by setting up a linear optimization on the real and imaginary parts of E_{occ} (Vanderbei *et al.* 2007, Cady *et al.* 2008) to constrain the intensity at the telescope pupil:

$$E_{\mathrm{occ}}(\rho;\lambda) = E_0 e^{ikz}\left(1 - \frac{2\pi}{i\lambda z}\int_0^R e^{\frac{\pi i}{\lambda z}(r^2+\rho^2)} J_0\left(\frac{2\pi r\rho}{\lambda z}\right) A(r) r \, \mathrm{d}r\right)$$

- Strict bounding should be $Re(E_{\mathrm{occ}}(\rho;\lambda))^2 + Im(E_{\mathrm{occ}}(\rho;\lambda))^2 \leq c$, with c an upper bound on the intensity; these are quadratic constraints on $A(r)$
- Bounding the real and imaginary parts independently introduces some slightly conservative assumptions, but assures the optimization remains linear.
- Linear optimizations have globally optimal solutions, so we get good apodization profiles with each run of the optimization rather than getting caught in local minima.
- Even better, we can use c as a variable and put it in the cost function, so we minimize the upper bound on the intensity.

Designing an occulter (VI)

We also add some constraints to ensure center of the occulter is solid (to ensure there is a place for the spacecraft bus) and the petal edges are smooth (as the optimization will tend to produce spiky bang-bang solutions otherwise). Can tweak further if desired.

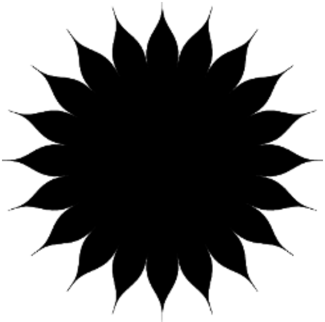
The full problem:

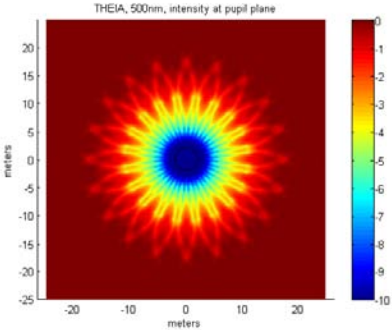
$$\begin{aligned}
\text{Minimize}: \quad & c \\
\text{subject to}: \quad & Re(E_{\text{occ}}(\rho;\lambda)) - c/\sqrt{(}2) \le 0 \\
& -Re(E_{\text{occ}}(\rho;\lambda)) - c/\sqrt{(}2) \le 0 \\
& Im(E_{\text{occ}}(\rho;\lambda)) - c/\sqrt{(}2) \le 0 \\
& -Im(E_{\text{occ}}(\rho;\lambda)) - c/\sqrt{(}2) \le 0 \\
& \forall \quad \rho \le \rho_{\max}, \quad \lambda \in [\lambda_{\min}, \lambda_{\max}] \\
& A(r) = 1 \quad \forall \quad 0 \le r \le a \\
& A'(r) \le 0, \quad |A''(r)| \le \sigma \quad \forall \quad 0 \le r \le R
\end{aligned}$$

Lastly, we choose N so $|E_{\text{bin}} - E_{\text{occ}}| \ll c$ for $\rho \le \rho_{\max}$.

Optimized shadow

Result: a dark shadow at the telescope aperture.





A note on IWA

Inner working angle (IWA): the closest angle to the optical axis at which we can detect a planet of a given brightness.

- For coronagraphs and interferometers, this value is wavelength-dependent.
- For an occulter, this is approximately set by geometry:

$$\text{geometric IWA} = \arctan \frac{R}{z} \approx \frac{R}{z}$$

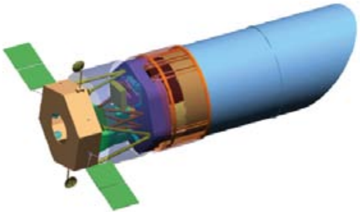
  and is *not* wavelength-dependent.
- For most occulters, the IWA is in the range of $75 - 150$ milliarcseconds (mas).

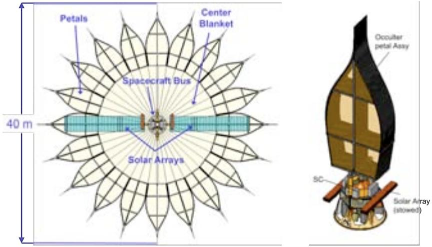
Point designs

THEIA

THEIA (Telescope for Habitable Exoplanets and Interstellar/Intergalactic Astronomy) (Kasdin *et al.* 2009)

- Developed as part of the Astrophysics Strategic Mission Concept Studies
- 4m on-axis UVOIR telescope designed to work jointly with an occulter
- 10m petals on a 40m diameter occulter
- Operates at two distances from the telescope, each providing data in a different spectral band





Top. ITT *Bottom.* Lockheed Martin

Scaling the system

Making an occulter work at two distances doesn't require any changes to shape.

$$z \rightarrow za \qquad\qquad \lambda \rightarrow \lambda/a$$

$$E_{occ}(\rho) = E_0 e^{\frac{2\pi i z}{\lambda}} \left(1 - \frac{2\pi}{i\lambda z}\int_0^R A(r) J_0\left(\frac{2\pi r\rho}{\lambda z}\right) e^{\frac{\pi i}{\lambda z}(r^2+\rho^2)} r dr\right)$$

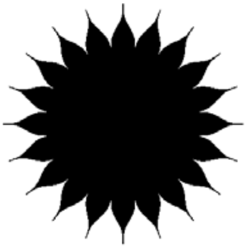
$$\Downarrow$$

$$E_{occ'}(\rho) = E_0 e^{\frac{2\pi i z a^2}{\lambda}} \left(1 - \frac{2\pi}{i\lambda z}\int_0^R A(r) J_0\left(\frac{2\pi r\rho}{\lambda z}\right) e^{\frac{\pi i}{\lambda z}(r^2+\rho^2)} r dr\right)$$

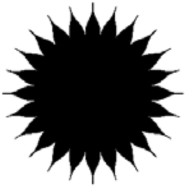
Result: same electric field, within a constant phase factor; band goes from $[\lambda_L, \lambda_H]$ to $[\lambda_L/a, \lambda_H/a]$. Downside: inner working angle goes from $\frac{R}{z}$ to $\frac{R}{za}$. For THEIA, goes from 75mas to 118mas.

Occulting Ozone Observatory: O_3 (Kasdin *et al.* 2010)

- Designed to fit within the cost cap for a probe-class mission
- Uses an off-the-shelf telescope (Nextview) available from ITT for approx. $50 million.
- Occulter is smaller, provides suppression 250 – 550nm
- Designed to find Earth-like planets and look for the presence of ozone
- Fits all in a single rocket fairing; THEIA requires two launches



THEIA (to scale)

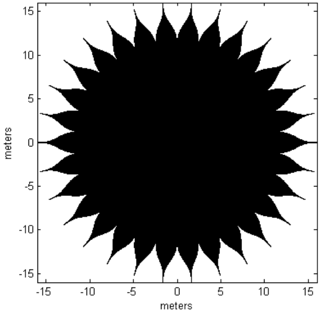


O3 (to scale)

Intermediate-scale: 1.5m O_3 variant

Between these two, can think about designs for mid-sized telescopes.

Example: an occulter for a 1.5m telescope, 250-550nm.



32m diameter, 6m petals.

A petal for this occulter design will be tested here at JPL:

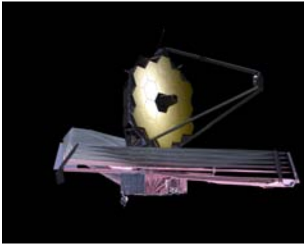
- being built out of flight-like materials (ultra-low-CTE composites)
- will performing edge metrology to ensure that it meets tolerances

Tolerances slightly loosened (to 3×10^{-10} from edge errors) for first test.

Both O_3-type designs can be used at two distances as well.

Occulters with JWST

Other studies look at using JWST (see *e.g.* Soummer *et al.* 2009)



- Capable of detection with NIRCam, spectroscopy with NIRspec.
- Occulters would be 60-70m, in light of the longer wavelengths and larger aperture
- Requires additional starshade hardware for steering, as can't add hardware to JWST
- Would require changes to optical filters in NIRSpec, possibly NIRCam to reduce out-of-band leak

Spanning the parameter space

The fact the same occulter works at two distances hints that not all of the input parameters to the optimization are independent. We can do a change of variables and rewrite the propagation integral in terms of independent nondimensional parameters:

$$r' \equiv \frac{r}{R}, 0 \leq r' \leq 1$$

$$\rho' \equiv \frac{\rho}{\rho_{\max}}, 0 \leq \rho' \leq 1$$

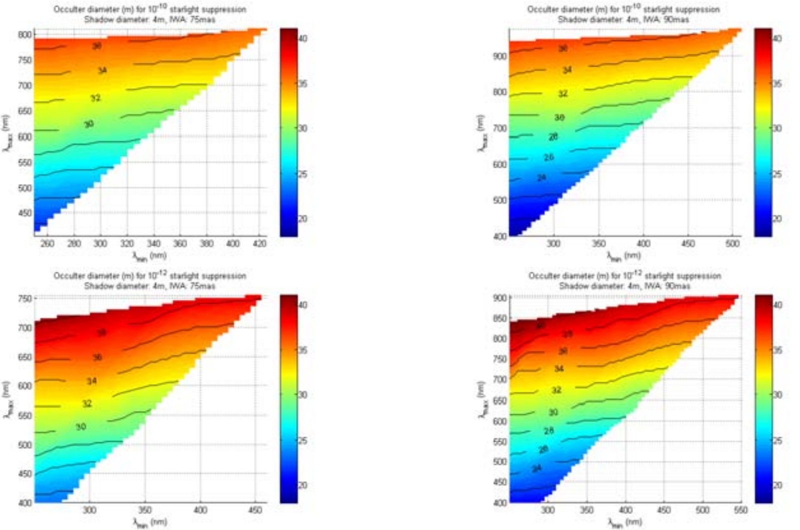
$$N_o \equiv \frac{R^2}{\lambda z}, N_1 \leq N_o \leq N_2$$

$$N_t \equiv \frac{\rho_{\max}^2}{\lambda z}, N_3 \leq N_o \leq \frac{N_3 N_2}{N_1}$$

$$E(\rho') = 1 + 2\pi i N_o \int_0^1 A'(r') J_0 \left(2\pi \sqrt{N_o N_t} r' \rho'\right) e^{\pi i \left(N_o r'^2 + N_t \rho'^2\right)} r' dr'$$

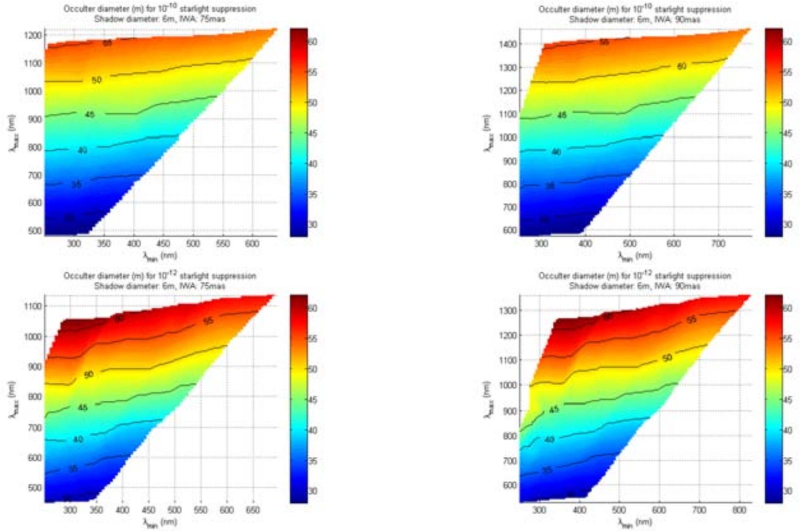
Three independent parameters bound N_o and N_t for broadband optimization, and let us examine the parameter space of possible occulters. We can mine this data to see what it takes for an occulter to meet desired science requirements.

Occulters for < 2m telescopes



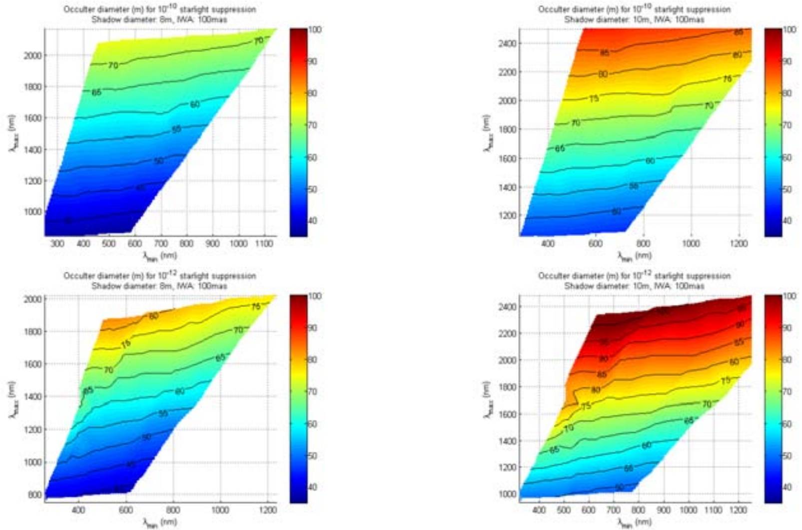
Color gives required occulter diameter.

Occulters for ∼4m telescopes



Color gives required occulter diameter.

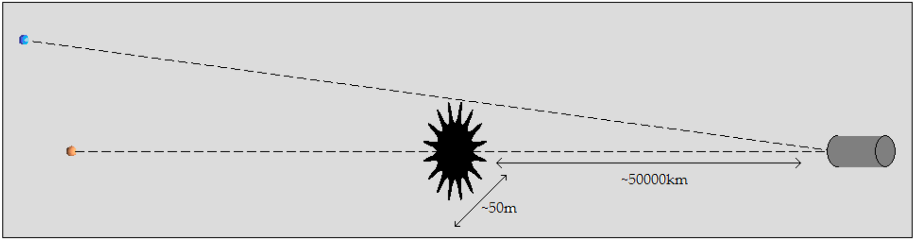
Occulters for > 6m telescopes



Color gives required occulter diameter.

Testing and verification

Testing occulter performance



Experimentally testing occulter optical performance at full-size is virtually impossible:

- Diameter is tens of meters
- Occulter-telescope distance is tens of thousands of kilometers

Instead, we make scale models to verify optical modeling on the ground and build full-scale petals to verify they meet the required optical tolerances. (This work is ongoing here at JPL and elsewhere.)

Scaling the system (again)

The general strategy for optical testing: scale the system down by keeping $\frac{r^2}{\lambda z}$ and $\frac{\rho^2}{\lambda z}$ constant:

$$z' \to z/a^2 \qquad r' \to r/a \qquad \rho' \to \rho/a$$

$$E_o(\rho) = E_0 e^{\frac{2\pi i z}{\lambda}} \left(1 - \frac{2\pi}{i\lambda z}\int_0^R A(r) J_0\left(\frac{2\pi r \rho}{\lambda z}\right) e^{\frac{\pi i}{\lambda z}\left(r^2+\rho^2\right)} r\,\mathrm{d}r\right)$$

$$\Downarrow$$

$$E_o(\rho) = E_0 e^{\frac{2\pi i z' a^2}{\lambda}} \left(1 - \frac{2\pi}{i\lambda z'}\int_0^{R'} A(ar') J_0\left(\frac{2\pi r' \rho'}{\lambda z'}\right) e^{\frac{\pi i}{\lambda z'}\left(r'^2+\rho'^2\right)} r'\,\mathrm{d}r'\right)$$

Result: same electric field, within a constant phase factor. a is on the order of 10^3-10^4.

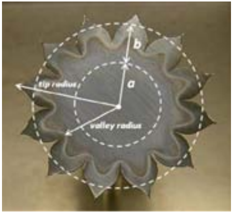
Overall design

Systems have three parts:

- A source to simulate the star
- A scaled-down occulter with a mount
- A detector (optionally with aperture and lens)

No other optics in the system. Approaches used now include:

Wire-mounted mask



Samuele *et al.* 2010

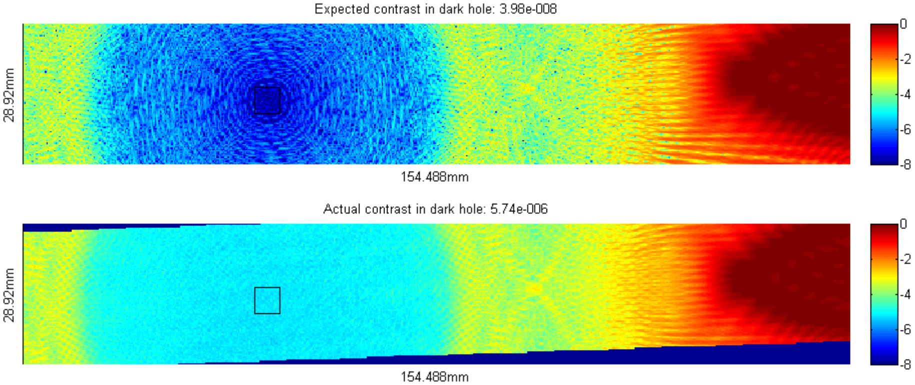
Mask with etched mount (made at MDL)

Cady *et al.* 2009

Testbeds at Princeton (Cady *et al.* 2009, 2010), NGAS (Samuele *et al.* 2009, 2010), University of Colorado (Schindhelm *et al.* 2007)

Subscale optical tests

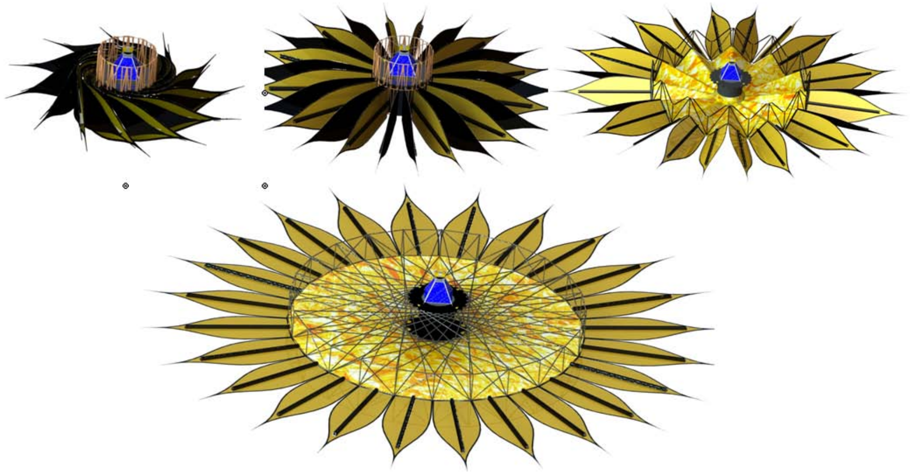
Slice through the pupil plane in simulation (top) and experiment (bottom) at 633nm:



Still looking at causes for extra light in the center.

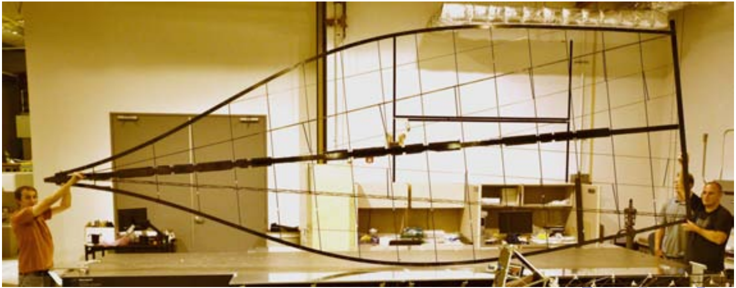
Mechanical design and deployment: O_3

Petals are wrapped around a central truss, unfurl and then fold down when the truss opens.



Deployment

A proof-of-concept model based on the 1.1m O_3 design was built at JPL, and the deployment was tested:

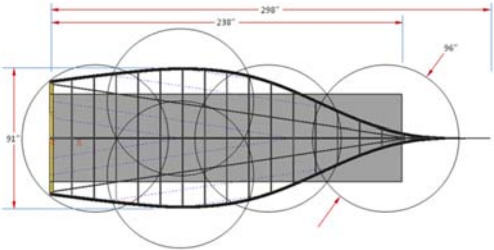


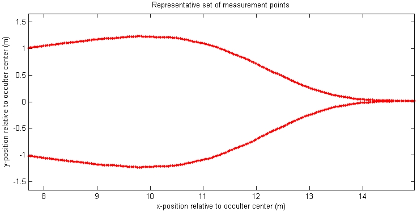
Petal deployment demonstration

Metrology tests

Currently, a petal for the 1.5m design is being constructed to test manufacturing tolerances.

Faro arm used to measure edge position





Tolerances for current TDEM study

For the petal currently being manufactured, the following tolerances are specified.

Perturbation	Requirement	Units	Mean Contrast
Proportional Width	0.0001	n/a	1.0E-10
Tip Clip	15	mm	4.2E-11
In-plane quadratic bend	20	mm	1.4E-12
1 cycle per petal symmetric	141.4	um	5.3E-11
2 cycle per petal symmetric	50.0	um	1.6E-11
3 cycle per petal symmetric	27.2	um	3.0E-11
4 cycle per petal symmetric	17.7	um	6.2E-11
5 cycle per petal symmetric	12.6	um	6.8E-12
Symmetric residual > 5 cycles	24.7	um	5.0E-13

Part of an allocation for a 10^{-9} occulter.

Only considering terms that can be investigated for a single petal; can't look at position errors, alignment errors, deployment errors...

Tolerances for THEIA

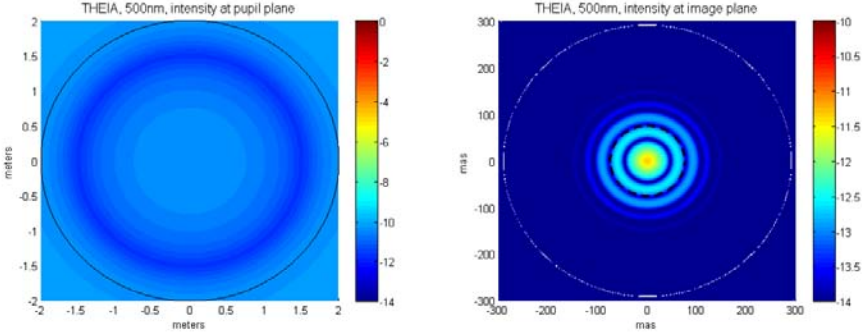
The following are a subset of the tolerances on position and shape examined for THEIA.

Petal Position or Shape Error	Allocation
r.m.s shape ($1/f^2$ power law)	100 μm
Proportional shape	80 μm at max width
Length clipping at tip	1 cm
Azimuthal position	0.003 deg (1 mm at tip)
Radial position	1 mm
In-plane rotation about base	0.06 deg (1 cm at tip)
In-plane bending (r^2 deviation)	5 cm
Out-plane bending (r^2 deviation)	50 cm
Cross-track occulter position	75 cm

Spergel *et al.* 2009, Dumont *et al.* 2009

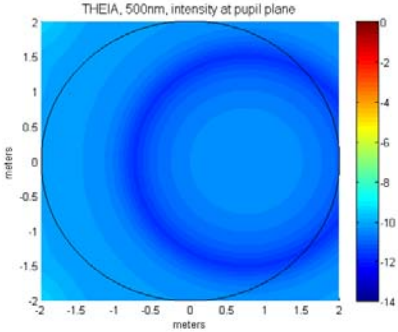
These are challenging, but not beyond the levels required for large deployable antennas in space now. Moreover, shape errors diffract light which is primarily confined to within the IWA, and can be mitigated further by spinning the occulter.

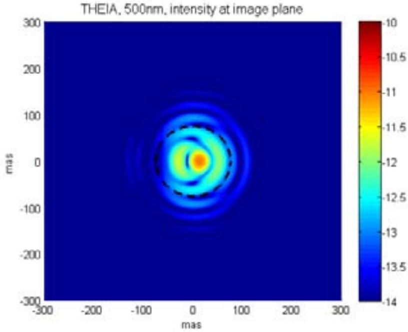
THEIA, performing ideally



Above, the pupil and image planes of THEIA without errors. We can introduce errors in occulter position, orientation, and shape, and look at how these errors change the image plane contrast.

Lateral shift (75cm)

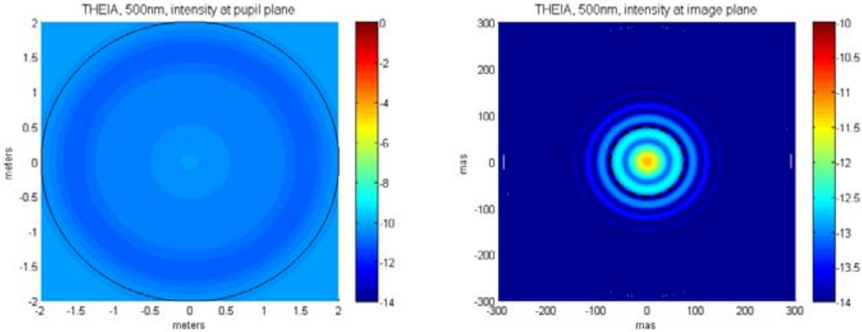




Shifts (and sources off the optical axis) can be modeled by modifying the pupil plane.

But perturbations are very slow; can do feedback control using low-resolution imagery in other bands.

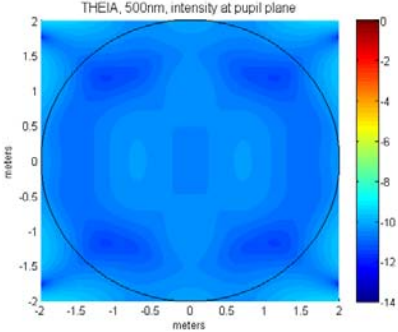
Separation distance shift (1000km)

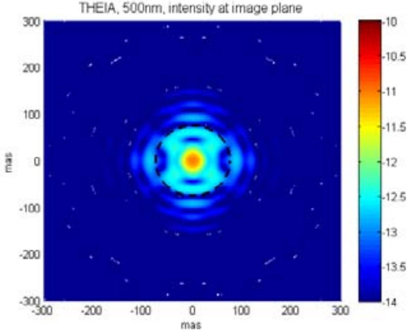


Changes in occulter-telescope distance require the integral to be recalculated with a different z, but tolerances are very high ($\sim$ 1000km) and can be enlarged further by adjusting the optimization bounds:

$$\lambda z = (z + \Delta z)\left(\lambda - \frac{\lambda \Delta z}{z + \Delta z}\right) = (z - \Delta z)\left(\lambda + \frac{\lambda \Delta z}{z - \Delta z}\right)$$

Occulter tilt (20°)

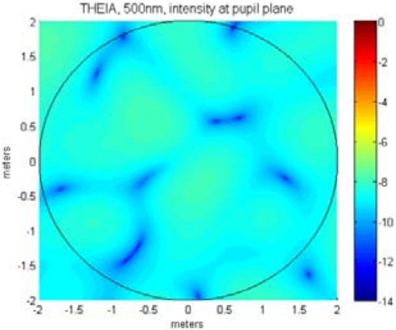


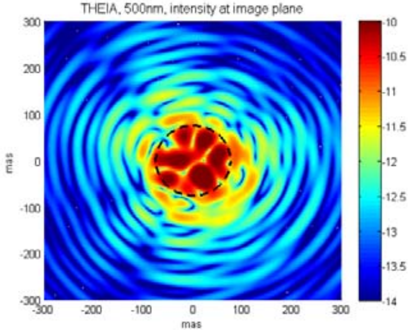


Occulter tilts, to a first approximation, can be modeled by compressing the occulter: taking the projection onto the plane perpendicular to the optical axis.

In general, a few degrees has little effect; orientation will be controlled much more finely than that.

Edge error (100μm rms, $1/f^2$ power law)





Inexact edges diffract a lot of light—need very precise manufacturing.

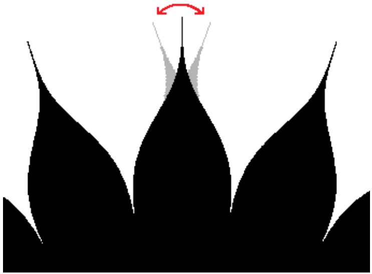
But not beyond the levels required for large deployable antennas in space now, and primarily confined to within the IWA.

Expect better understanding of the edge errors after current study.

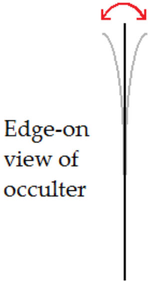
Bending modes

We separate bending modes into two major classifications for error budgeting:

In-plane bending

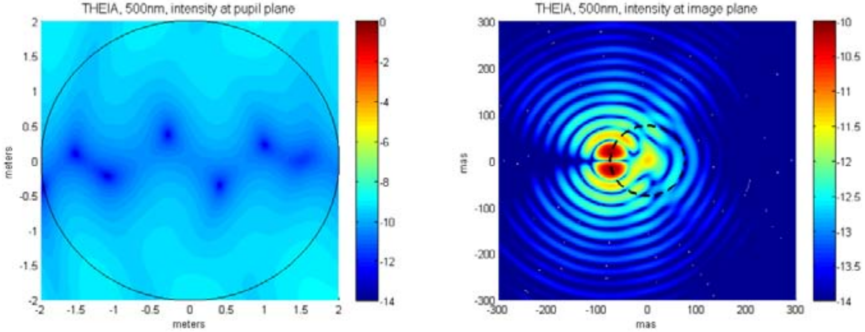


Out-of-plane bending



Exact modes can be determined from finite-element modes of the occulter; currently being modeled here at JPL (see for example Jordan *et al.* 2009).

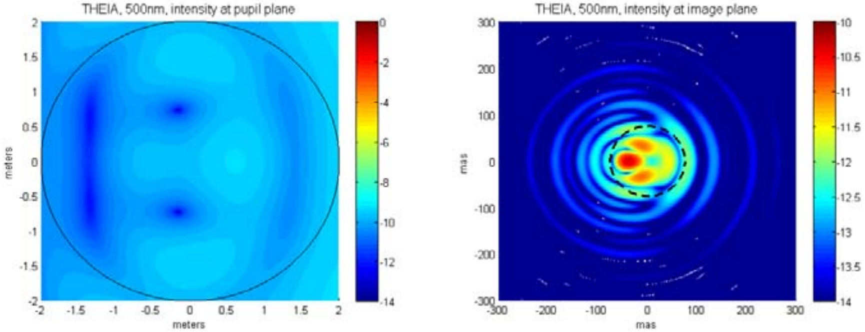
In-plane bend (500μm, quadratic profile)



Petals have to be well-placed in the plane—if they bend back and forth in the plane, they diffract light into places in the image plane where they could be confused with planets.

Again, this is difficult but not beyond state-of-the-art, and in-plane modes are smaller than out-of-plane modes.

Out-of-plane bend (1m, linear profile)



Petals bending up and down can also change the effective shape, and these are more natural vibrational modes for disks.

However, the out-of-plane tolerances are also much larger.

Future occulter work

Next steps for general occulter work:

- thermal-mechanical-optical simulations
- edge manufacturing and testing
- end-to-end formation flying simulations
- material testing
- further deployment testing...

Thanks to my collaborators and coworkers at JPL, Princeton, and elsewhere.

Thank you for your attention; I'd be happy to take any questions.